The use of small-scale constructed wetlands to treat greywater in residential households for use in activities that require non-potable water

By

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A dissertation submitted in partial fulfilment of the requirements for the degree

MASTER OF SCIENCE

in

AQUATIC HEALTH

in the

FACULTY OF SCIENCE

at the

UNIVERSITY OF JOHANNESBURG

SUPERVISOR: DR. A. NEL

January 2019

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Acknowledgements

I would like to extend my thanks and acknowledgement to the following people and organisations, in no particular order, without whom the completion of my studies would not have been possible.

Rand Water, for funding this project, and for providing me with the resources, equipment and space for conducting this research.

The University of Johannesburg, for providing me with the opportunity to further my studies.

My Supervisor, Doctor Amina Nel (University of Johannesburg) for her continuous support, guidance, patience, intellectual knowledge, kindness, and advice. The standard and quality of my work is a result of Dr Nel's unwavering attention to detail and extensive knowledge.

My Direct Manager, Meagan Donnelly (Rand Water) for her support and advice throughout the duration of my research.

My Departmental Manager, Leslie Hoy (Rand Water) for his interest, support, and advice throughout the duration of my research.

Staff from GIBB, for their assistance with construction and design of the constructed wetlands used in this research.

Staff from Rand Water's Analytical Services department, for their assistance with the processing and analysing of my water samples.

Gregg van Rensburg, for his advice and assistance with my statistical analyses.

My Rand Water colleagues and fellow students for their support, advice, and laughter through difficult times and long hours.

My partner, family, and friends, for never doubting my abilities, even though I often did.

Abstract

The aim of this research was to test the effectiveness of three small-scale constructed wetlands (CW) on the treatment of residential household greywater of different sources. The main objective was to analyse and compare pre- and post-treatment greywater for parameters such as pH, pathogens, total dissolved solids (TDS), nitrates (NO_3), sulphates (SO_4), total phosphorous (TP), sodium (Na), boron (B), calcium (Ca), magnesium (Mg), oil and grease, total organic carbon (TOC), and other parameters for treatment efficiency. The design and construction of the wetlands was written up in a manual for use by residential home owners for the treatment of greywater to standards suitable for use in irrigating the garden and for other activities that require non-potable water. Three sub-surface flow (SSF) horizontal CW were designed and constructed on site at Rand Water's Environmental Management Services Nursery. Each system was planted with a variety of indigenous wetland plants. The systems were constructed adjacent to greywater sources, namely office kitchens and bathrooms. Only basin water, kitchen sink water, and shower water was used for treatment. Samples of pre- and post-treatment greywater were taken over a period of 9 months in 2017/2018. Samples were analysed at Rand Water's laboratory (SANAS-accredited). Results of the research showed that CW were efficient at removing organics and nutrients from the greywater influent, showing a significant decrease in TOC for the main office artificial wetland (MO-AW), nursery artificial wetland (N-AW) and Zwartkopjes artificial wetland (Z-AW), oil and grease for the MO-AW and N-AW, TP for the MO-AW and N-AW, and SO_4 for the MO-AW. There was also a significant decrease in B post-treatment for the N-AW, in *E. coli* counts for the MO-AW, turbidity for the MO-AW and N-AW, and TDS for the MO-AW. Overall, concentrations of most pollutants post-treatment fell within the accepted range for long-term and sustainable use of treated greywater for drip irrigation of small-scale crops and household gardens, according to the Target Water Quality Range (TWQR) for the Water Quality Guidelines for Irrigation (WQG/I). The results of this research show that easily implementable, sustainable, and aesthetically-pleasing greywater treatment solutions are available to the homeowner that they will be able to implement and maintain themselves.

Keywords: constructed wetlands; domestic greywater use; greywater; household gardens; irrigation.

Chapter 1: Introduction

1.1. Background and motivation

South Africa (SA) is a semi-arid country where freshwater is distributed unevenly over space and time, and the annual demand for potable water is increasing annually with an increase in urbanization and development, with a resultant reduction in net freshwater resources (Ilemobade *et al*., 2012). While the country has a well-developed network of water infrastructure, the demand for available water is fast approaching capacity and the availability of sites for new infrastructure is diminishing (National Water Resource Strategy, 2013). South Africa's freshwater resources are naturally exposed to what is termed high hydro-climatic variability over space and time, and this places a constraint on the availability of water for economic development and sustainability in the country (Schulze, 2012). Access to potable water is a challenge faced by many South Africans, a situation that worsens when the country is hit by droughts and faulty infrastructure (Bakare *et al*., 2017). In the last ten years, potable water demand in SA has increased from 22% to 27% (NWRS, 2013), indicating the pressure the country's resources are under. Schulze (2012), emphasises the importance and need to address SA's water sector and its short-falls immediately, especially because of the anticipated effect that climate change is expected to have on the country's water resources, such as:

- A large percentage of the country's population is impoverished and particularly vulnerable to the potential effects of climate change;
- South Africa's fragile terrestrial and aquatic ecosystems are reliant on water supply; and
- The main effects of climate change are expected to be felt by people, ecosystem, and the economy as a result of its impact on water resources (Schulze, 2012).

Rand Water is Africa's largest potable bulk water supplier, and was established in 1903 in response to the demand for water in the rapidly expanding city of Johannesburg. Rand Water currently supplies over 3 600 million litres of water a day to customers in four provinces (Stelli, 2018). The drought of 1995 created a need for water awareness and conservation in Rand Water's area of supply, and Rand Water's environmental brand 'Water Wise' was initiated as a result. In addition, Rand Water, as a water board, is mandated by The Water Services Act 108 of 1997 (WSA) (Department of Water Affairs and Forestry (DWAF), 1997), to show the following:

- *"Section 4.2.c. (vi) measures to promote water conservation and demand management;*
- *Section 33. (vi) water conservation and the prevention of wasteful or unlawful use of water provided by the water board; and*
- *Section 39. an environmental policy, including measures to reduce water wastage to an acceptable level; and the measures, including public awareness campaigns, to be taken."*

The Water Wise section addresses the above mandate by providing awareness and educational campaigns to the public. The team consists of environmental educators, researchers, trainers, and community liaison partners that work with end-users to inform and educate the general public on SA's water situation. Campaigns, information pamphlets, workshops, and events are used to convey information on water-use efficiency in the home, school, garden, and office. Water Wise and Research (WW and R) is a branch of the brand that focuses on awareness amongst the adult market, water conservation, and environmental research (Leslie Hoy *pers. comm*., August 2011).

Greywater is fast becoming an effective solution to the need for non-potable water, and is gaining interest in SA (Bakare *et al*., 2017). Greywater provides an easily accessible, free, and dependable source of water (Engelbrecht and Murphy, 2006). The re-use of wastewater is beneficial in a water-scarce region, as it can satisfy fast-growing water demands, while conserving potable water (Gemmell and Schmidt, 2010). Greywater re-use can be seen as a valuable tool to reduce water stress in water scarce countries, acting as a measure to conserve potable water at a household level, and reduce wastewater treatment workloads (Ghaitidak and Yadav, 2013). Greywater is increasingly being used for irrigation in households, partly because it is of better quality than wastewater and does not require extensive treatment processes before it can be used (Gross *et al*., 2005). The Department of Water and Sanitation (DWS) recognise that water demand in SA can be expected to increase by at least 1.2% over the next decade (NWRS, 2013). Gemmell and Schmidt (2010), have identified the need for an increase in greywater re-use, specifically for irrigation in agriculture in a water-scarce country such as SA, and suggested more research into cheap and effective wastewater treatment processes to reduce pathogens in wastewater used for irrigation.

While the use and disposal of greywater has largely been neglected in South African legislation, greywater can provide a cost-effective and sustainable solution to the need for a reduction in consumption of potable water. This will reduce the pressure on SA's already dwindling freshwater resources. One of the priority research questions posed by a collaborative process with a wide range of water specialists, is the investigation of the most cost-effective and hygienic technology for treating and disposing of greywater, specifically in low-income areas (Rodda *et al.*, 2010).

Constructed wetlands (CW) are viewed as the most efficient and environmentally-friendly method of treating and processing wastewater such as greywater (Li *et al*., 2009). However, these systems are sometimes regarded as too large to be suitable for implementation in urban areas (Li *et al*., 2009). Information on the efficiency with which CW treat greywater is lacking, with little known about the reliability and efficiency of performance of these wetlands, or the optimal design technologies for effective greywater purification (Frazer-Williams, 2007). This research project aims to investigate the use of small, sub-surface flow (SSF) CW to treat greywater from kitchen and bathroom effluents at a scale suitable for the implementation in urban, suburban and community spaces, landscapes and gardens.

Water Wise has conducted a number of market research surveys with members of the public in an effort to understand the general perception of the water situation in SA and how people address the issue. Preliminary results from surveys conducted between 2015 and 2016 of approximately 1 260 respondents indicated that only 13% of the people interviewed re-use greywater for activities that require non-potable water in their home. However, 60% of those surveyed indicated an interest in learning more on how to treat and re-use greywater in the home. It is anticipated that this research project will provide guidelines on how to simply and effectively treat greywater in a manner that can be easily implementable in the home. This will in turn empower the general public to improve their water use habits, and in addition, fulfil Rand Water and Water Wise's legal mandate.

1.2. Study hypothesis, aims, and objectives

1.2.1. Hypothesis

Null hypothesis (H_0)

Constructed wetlands (CW) can effectively treat household greywater by significantly reducing contaminants to a standard suitable for re-use in activities that require non-potable water, such as garden irrigation.

Alternative hypothesis (H_1)

There is no significant difference in the water quality of household greywater before and after treatment with CW.

1.2.2. Aim of the study

The primary aim of this research is to test the effectiveness of three small-scale CW on the treatment of greywater of different sources, namely kitchen sink, bathroom basin, and shower greywater.

1.2.3. Objectives

Objective 1: Implement three CW on site at Rand Water's Environmental Management Services Department at locations that are accessible for the treatment of typical 'household-type' greywater such as kitchen sink, bathroom basin, and shower greywater.

Objective 2: Collect samples of the greywater before and after treatment by the CW. Analyse the samples for various water quality parameters.

Objective 3: Use the results of the water quality analyses to determine if the CW significantly reduce the concentration of contaminants in greywater, or improve water quality, to indicate the effectiveness of the wetlands to 'treat' greywater to a standard suitable for re-use in garden irrigation.

Objective 4: Develop a manual for the assembly of small-scale CW that can be set up easily by residential home owners. This manual will be used in future awareness and education campaigns to promote the use of CW to treat household greywater.

1.3. Study overlay

Chapter 1: Introduction. This chapter provides an introduction to the research project and its aims and objectives. It includes a background to the topic, as well as a motivation for the research undertaken, and the study hypothesis.

Chapter 2: Literature review. This chapter reviews previous work that has been done on this topic, starting from a global perspective, and narrowing down into a national, and local view. Topics discussed include SA's water situation, the re-use of household greywater, water legislation, water quality standards and guidelines, the treatment of greywater with CW, and case studies that have analysed similar research.

Chapter 3: Materials and methods. This chapter focuses on the methodology used to conduct the research and analyse the recorded data. Specifically, water quality sampling and analysis is discussed, as well as the statistical analyses of the results. Included in this chapter is a description of the study area.

Chapter 4: Results. This chapter looks at the analysis of the results from the water quality samples. Results are statistically analysed and presented in tables and graphs.

Chapter 5: Discussion. Results from the study are discussed with relevance to the initial aims, objectives, and hypothesis, as well as other related studies.

Chapter 6: Conclusion. The results of the research are summarised and concluded in this chapter, and related back to the aims and objectives of the study. The study hypothesis is addressed here. In addition, recommendations for further studies and research on this topic are mentioned.

Chapter 7: References: This chapter is a list of references used throughout the dissertation.

1.4. Expected results

It is envisioned that this research will provide an effective, sustainable and aesthetically-pleasing greywater treatment system that the average homeowner will be able to implement and maintain themselves. A manual will be developed that can then be distributed to the general public, detailing the materials and methods required to implement the system. This may be done in conjunction with training offered by Water Wise at various home and décor events and shows. It is anticipated that this research will further highlight the efficiency of CW in the treatment of domestic greywater to a standard suitable for use in garden irrigation. Extensive market research already conducted by Water Wise has shown that the general public would prefer to know more about greywater use in a household setting and need to feel empowered to make a difference to the water situation in SA. This research should fulfil both those needs. In addition, the systems can be marketed to the public as a property-enhancing feature.

Chapter 2: Literature review

2.1. Global water situation

The need for conservation of high quality freshwater and the increasing pressure on world-wide water resources has encouraged the re-use of wastewater and greywater as an integral part of water demand management (Avery *et al*., 2007; Donner *et al*., 2008; Al-Hamaideh and Bino, 2010). The availability of freshwater globally, and especially in drier regions such as Africa and South Asia, has decreased, and the issue of both water quality and quantity has become a concern as the world moves towards a water crisis (Blumenthal *et al*., 2000). A recent report by United Nations Economic and Social Council (UNESC) (2017) highlighted the fact that more than 2 billion people worldwide live in water-stressed countries, with a potential for future water scarcity. A number of countries worldwide, such as Australia, Britain, the Netherlands, and the USA have experimented with reusing wastewater and greywater to address water stress and water scarcity (Engelbrecht and Murphy, 2006). Raw wastewater sources available for re-use include greywater, municipal or domestic wastewater, and rainwater (Frazer-Williams, 2007).

2.2. South Africa's water situation

South Africa (SA) is classified as a semi-arid and water-stressed country, with very variable rainfall distribution patterns both temporally and spatially. The country receives an annual mean rainfall of approximately 450 mm (Schulze, 1997). South Africa is also described as water scarce, which means the country's water supplies have fallen below 1 000 m^3 available potable water per person per year (United Nations (UN), 2012). This has placed great pressure on the country's freshwater resources (Bakare *et al.,* 2017), as well as the natural systems' ability to provide the quantity and quality of water required as a result of overpopulation, urbanization and industrialization (Carden *et al.,* 2007a). Within the last two years, the country has experienced one of the worst droughts of the century, which has been linked to climate change and the El Niño weather phenomenon (Botai *et al.,* 2016). The resulting decrease in rainfall and rise in temperatures has led to the implementation of urban water restrictions and has decimated the country's agriculture (Botai *et al.,* 2016). The general public have been encouraged to implement water-saving behaviours and drastically reduce water consumption (Petterson, 2016) in order to reduce pressure on potable water supply. One of the behaviours that is viewed as wasteful and that has been discouraged is the watering of gardens using potable water. Water is already a limiting factor to development in southern Africa (Mukheibir, 2005). South Africa (SA) has a shortage of potable water, the requirement of which is critical to sustainable development and economic growth (Bakare *et al.,* 2017).

Climate variability, such as extreme flooding events and drought, coupled with high seasonal and temporal variations in rainfall and high run-off and evaporation rates compounds the pressure on SA's water resources by an ever-increasing population (Mukheibir, 2005). Recently, South African water authorities have begun focusing on water re-use and recycling schemes to address the critical need for freshwater in sustainable development and economic growth of the country (Bakare *et al.,* 2017). The Strategic Framework for Water Services, set out by the Department of Water Affairs (DWA) in 2003, developed targets for the provision of basic water and sanitation for South African citizens in the long-term (Carden *et al*., 2007a).

Mukheibir (2005), highlights a number of key factors affecting water availability in SA, namely, the country's variable rainfall and low run-off; an increase in economic development and population growth, which has led to an increase in water demand and pollution; and the management of this resource by the relevant authorities. There is a definite need for sustainable, efficient and cost-effective greywater treatment systems that are economical to construct, and require minimum maintenance (Wurochekke *et al*., 2015). The use of greywater can significantly decrease the pressure on water resources by lowering freshwater consumption (Benami *et al*., 2016) and is one of the main options for a new source of water, especially in regions suffering from water scarcity (Blumenthal *et al*., 2000). The re-use of greywater is a demand-side management strategy that has been promoted at a domestic level to reduce end-user water demand, relieve pressure on wastewater treatment works, and to a lesser extent, contribute to groundwater recharge (Mukheibir, 2005). According to Ilemobade *et al*. (2012), there are a number of additional advantages to the re-use of greywater for activities that use non-potable water, such as:

- Reducing the pressure on potable water supplies for activities that do not require potable water;
- The provision of non-potable water in remote areas where municipal potable water supplies are not reliant;
- Reducing the volume of wastewater that is sent to wastewater treatment works and thereby reducing the pressure on these systems;
- Reducing the potential for wastewater to be discharged into surface water bodies; and
- Using nutrient-enriched suitably treated wastewater to benefit agriculture.

2.3. Water quality standards

The South African Water Quality Guidelines were developed by DWAF approximately 22 years ago in response to the need to specify water quality required for different water uses, fitness for use of water, and for general water quality management purposes. There are seven volumes that fall under the guidelines (DWAF, 1996d), namely:

- Domestic water use;
- Recreational water use;
- Industrial water use;
- Agricultural water use for irrigation;
- Agricultural water use for livestock watering;
- Agricultural water use for aquaculture; and
- Water quality for aquatic ecosystems.

These guidelines are useful in determining whether water of a certain quality is fit for use, depending on the requirements listed in each volume, and specific to each activity that requires water.

2.4. Greywater

It is important to distinguish between the different waste streams that are produced in a domestic household setting, as each waste stream contains different characteristics and pollutant loads and therefore will require different treatment processes (Donner *et al*., 2008). Greywater (Table 1) can be defined as domestic wastewater that has lower concentrations of the bacteria and chemicals found in combined household wastewater. For example, wastewater from the kitchen generally has a high concentration of bacteria, organic carbons, and solids, as well as fats, oils and grease, while shower and bathroom basin greywater usually has a much lower concentration of bacteria and chemicals (Doughten, 2010). Many households re-use their greywater by passing it from the source (i.e. washing machine; shower; bath) through plumbing pipes and into the garden where required; this is more accurately referred to as greywater disposal and not greywater irrigation (Roesner *et al.*, 2006).

Table 1. General characteristics of domestic greywater (adapted from Ecosan Services Foundation (ESF), 2008).

Item	Range in values contributed in greywater
Biological oxygen demand, 5 days, 20°C (BOD_5) (mg/L)	45 - 54
Chemical oxygen demand (COD) (mg/L)	1.6 - 1.9 x BOD_5
Total organic carbon (TOC) (mg/L)	0.6 - 1.0 x BOD_5
Total solids (mg/L)	170 - 220
Suspended solids (SS) (mg/L)	70 - 145
Grit (inorganic, 0.2mm and above) (mm)	5 - 15
Grease (mg/L)	10 - 30
Total nitrogen (N) (mg/L)	6 - 12
Organic N (mg/L)	~0.4 x total N
Free ammonia (NH_3) (mg/L)	~0.6 x total N
Nitrite (NO_2) (mg/L)	-
Nitrate (NO_3) (mg/L)	0.0 - 0.5 x total N
Total phosphates (TP) (mg/L)	0.6 - 4.5
Organic phosphorous (P) (mg/L)	~0.3 x total P
Inorganic (ortho- and polyphosphates) (mg/L)	~0.7 x total P
Potassium (K) (as K oxide K_2O) (mg/L)	2.0 - 6.0

The concept of water re-use has been slow to develop in SA, and it is only recently that South African water authorities have started placing more emphasis on water re-use and recycling (Bakare *et al*., 2017). Carden *et al*. (2007a), discovered that amongst both urban and rural South African settlements, a number of people view greywater as dirty and unhealthy, and do not feel it can be re-used. If greywater is managed, it is generally thrown out onto the surface of the ground, which can have serious implications for human and environmental health. In addition, in areas with stands that are too small for gardens, residents do not see the benefit in re-using greywater and see it more as a potential problem (Carden *et al*., 2007a). However, with an increase in urbanisation comes an increase in water use, which results in an increase in the region's wastewater stream. This wastewater needs to be treated to prevent human and environmental health issues from occurring (Gemmell and Schmidt, 2010), especially if the waste stream is disposed of in a haphazard and uncontrolled manner.

If used water such as domestic greywater is released untreated into water bodies, it can result in contamination and eutrophication (Wurochekke *et al*., 2015). However, if used in a manner that is protective of both human and environmental health, re-using greywater can assist in the conservation of a very limited natural resource, while also encouraging buy-in to the 'recycle and re-use' ethos (Droughten, 2010).

Reclaimed wastewater, such as the re-use of domestic greywater, can be used for non-potable applications such as flushing toilets (Avery *et al*., 2007), especially in countries where potable water is used primarily to flush toilets (Erikkson *et al*., 2002). Appropriately treated greywater can also be used to wash paths, walls or vehicles, irrigate lawns and gardens (Queensland Government, 2008), for fire protection, washing of windows, and concrete production (Okun, 1997). Before re-using greywater it is important to understand the quality of greywater before and after treatment, as well as potential contaminants that may occur in greywater, and their effect on human and environmental health. Greywater is a slightly contentious area of study, partly because the characteristics of greywater can vary so greatly from home to home, which affects treatment requirements and the extent of its application.

2.4.1. Greywater guidelines

Standardizing guidelines for greywater quality is difficult, as the chemical and biological characteristics of greywater can vary largely based on its source (Droughten, 2010). Many countries still do not have well developed legislation that addresses wastewater/greywater re-use and recycling (Donner *et al*., 2008). Most importantly, standards for greywater quality and its use must be set to ensure the safety of human and environmental health (Wurochekke *et al*., 2015). Carden *et al*. (2007a), suggested when optimising greywater management, that two main issues need to be addressed, specifically, creating a beneficial use from greywater such that it does not constitute a hazard; and having support in place to address a crisis situation where greywater use becomes a hazard, such as in high-density settlements.

Australia have legally implemented a guideline of the effluent quality criteria for greywater use, which includes where appropriately treated greywater can be used, as well as the technical and regulatory requirements for the installation of greywater treatment plants and use facilities (Queensland Government, 2008). The United States Environmental Protection Agency (USEPA) guidelines for domestic greywater quality are also very stringent (Avery *et al*., 2007).

Currently, there are no national guidelines that address the re-use of greywater in SA. Certain municipalities have developed guidelines around the use and disposal of greywater to prevent negative impacts on human and environmental health, such as the City of Cape Town and eThekwini Metropolitan (Ilemobade *et al*., 2012). While South African legislation may not directly address the re-use of greywater and does not directly object to its use, greywater is indirectly referred to in terms of the Health Act No. 63 of 1977 and the National Water Act No. 36 of 1998 (NWA), in terms of '*nuisances*'. Nuisances are regarded as fly or mosquito breeding, objectionable odours, surface ponding of water, and the flow of polluted water into a neighbouring property. The NWA also refers to the '*disposal of waste or water containing waste*', which may also indirectly refer to greywater disposal (Engelbrecht and Murphy, 2006). The WSA has a revision that speaks directly to the disposal of greywater, whereby "*a water services institution may impose limitations on the use of greywater if the use thereof may negatively affect health, the environment or available water resources*" (Ilemobade *et al*., 2012).

As per Australian greywater guidelines, it is not advisable to store greywater for longer than 24 hours as storage may encourage the growth of microorganisms and may cause offensive odours (Queensland Government, 2008). Droughten (2010), listed a number of other precautions to observe when using greywater:

- If used for irrigation, greywater should not come into direct contact with edible plants;
- Greywater used for irrigation needs to be applied to the soil below a layer of mulch or soil at least 5 cm deep, preferably as drip irrigation;
- The direct contact between humans, domestic pets and greywater needs to be prevented or minimized as far as possible;
- Buffer zones should be established between properties that utilize greywater and any surface water, stormwater systems, or other properties;
- Greywater from the kitchen must be passed through a primary treatment system designed to catch and hold back grease, oil, food scraps, and other solids;
- No spray irrigation of greywater should occur;
- Greywater must not be allowed to pool;
- No greywater run-off onto adjacent properties should be allowed;
- Greywater must not be discharged directly into any surface water bodies;
- Untreated greywater may be used for sub-surface irrigation of lawns and landscapes, sub-surface irrigation of food crops (except root crops) and composting;
- Treated greywater may be used for landscape ponds, toilet flushing, and CW; and

- Treated and disinfected greywater may be used to wash cars and other machinery and equipment, to flush sewer lines, in construction for dust control, ground cutting, and concrete cutting, and for large scale agricultural irrigation.

Carden *et al*. (2007b), suggested a number of additional considerations when handling greywater, specifically in terms of human health, namely, preventing greywater from coming into contact with potable water, preventing the use of greywater in households where residents may suffer from infectious health conditions, reducing irrigation with greywater if the soil is already saturated, ensuring that vegetables and fruit irrigated with greywater are thoroughly washed and cooked before consumption, and ensuring that hands are washed after contact with greywater.

Standards on greywater quality generally focus on total/faecal coliforms and *Escherichia coli*, organic content indicated by biological oxygen demand (BOD), turbidity or suspended solids (SS), and pH (Avery *et al*., 2007). The NWA discussed the quality of irrigation water that is lawfully permitted, which can apply to irrigation using greywater, as per the following standards:

- Electrical conductivity (EC) must not exceed 200 mS/h;
- pH must be between 6 and 9;
- Chemical oxygen demand (COD) must not exceed 5 000 mg/L;
- The faecal coliform count must not exceed 100 000 counts per 100 mL; and
- The sodium adsorption rate (SAR) must not exceed 2 (Engelbrecht and Murphy, 2006).

Rodda *et al*. (2010), suggested that the legal status of greywater for use in irrigation must be clarified and users need to be provided with guidance before greywater use can be promoted. This may also encourage the general public to embrace the treatment and use of greywater as a viable alternative to the use of potable water.

2.4.2. Household greywater

Greywater that is comprised of wastewater from kitchen sinks, laundry water, and bath and shower water, but excludes toilet wastewater, makes up between 50 and 80% of total residential wastewater (Al-Jayyousi, 2003). This portion of household wastewater is all potentially available for re-use (Rodda *et al*., 2010). Queensland Government (2008) in north-eastern Australia excluded kitchen water from greywater classification as it may contain food particles, oils, fats, and other wastes that could cause the growth of microorganisms and blockages of treatment systems. Kitchen water is often more polluted, can be more difficult to degrade, and may contain higher counts of pathogens compared to domestic wastewater such as washing and laundry water (Avery *et al*., 2007). Ecosan Services Foundation (ESF) (2008) summarised household greywater and distinguished between three sources (Table 2).

Table 2. Three main sources of household greywater determined by specific activities using water (adapted from ESF, 2008).

Greywater sources and their generic characteristics		
Kitchen	Laundry	Bathroom
• Food residue. • High amounts of oil, fat, and dishwashing detergent. • Drain cleaners and bleach. • High in nutrients and SS • Alkaline. • High in salt concentration.	• High concentrations of sodium (Na), phosphorous (P), surfactants, and nitrogen (N). • Bleach. • Oil. • Paints. • Solvents. • Non-biodegradable clothing fibre. • High concentration of SS. • Can contain pathogenic microorganisms.	• Considered the least contaminated source. • Soaps. • Shampoos. • Toothpaste. • Body care products. • Shaving waste. • Skin. • Hair. • Body-fats • Lint. • May contain traces of urine and faeces. • May be contaminated by pathogenic microorganisms.

2.4.3. Greywater use and disposal in South Africa (SA)

The re-use of greywater is an appealing concept in semi-arid and arid regions that experience regular water scarcity, fluctuations in rainfall, and an increase in water pollution (Al-Jayyousi, 2003). It has become popular for use in flushing toilets and irrigating gardens worldwide (Roesner *et al.*, 2006). As greywater contains substantially lower concentrations of pathogens compared to blackwater (this is wastewater that includes toilet water), there is less of a need for pre-treatment of greywater, and with careful management greywater can be a useful resource for irrigation (Engelbrecht and Murphy, 2006). The use of greywater for irrigation of both food and ornamental gardens can assist in supplementing rainwater as a source of water, especially in a semi-arid country such as SA.

Carden *et al*., (2007b), have developed a decision tree (Figure 1) with the aim to assist decision makers with determining the most suitable method for the disposal of greywater, whether it be on-site or off-site disposal. It has been suggested that residents and municipal planners require assistance in understanding the management options available for greywater in order to reduce any negative impacts of its use and/or disposal. In addition, SA's policy makers also need guidelines for the development of greywater management strategies in terms of the rate of greywater generation and how this will affect water and sanitation services (Carden *et al*., 2007b).

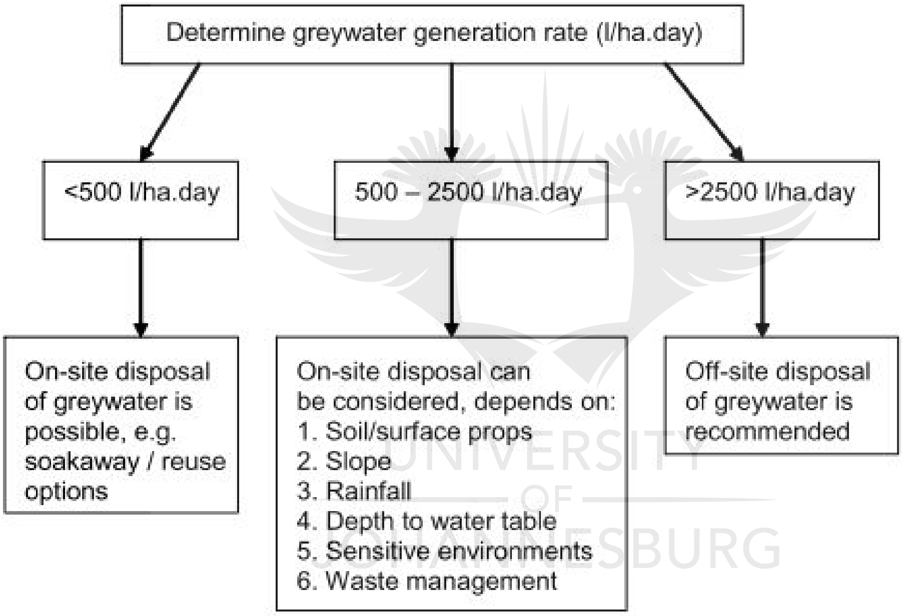

Figure 1. The greywater decision-tree assists with determining whether greywater should be disposed off-site or on-site (Carden et al., 2007b).

In a study on the use and disposal of greywater in South African settlements, Carden *et al*. (2007b) found that the quantity and quality of greywater produced is influenced by the socio-economic circumstances of the household. Generally, greywater is disposed of directly onto the ground in both rural and urban settlements, and the residents of some rural settlements prevent human and environmental health impacts by transporting greywater to nearby stormwater canals (Carden *et al*., 2007b).

2.4.4. Greywater for irrigation

The quantity of greywater generated in a typical household of four people is usually enough to irrigate non-grassed areas in the garden of a stand-alone house, namely flowerbeds and shrubs, but excluding lawn areas (Roesner *et al.*, 2006). While the use of treated greywater for irrigation may reduce the need for the utilization of natural freshwater resources, there may be resultant environmental problems, such as an increase in salinity and sodium (Na) content in soil and the accumulation of oil and grease (Al-Hamaideh and Bino, 2010).

Untreated greywater used for irrigation can result in the accumulation of salts and surfactants in the soil and can be toxic to plants over an extended period of time (Gross *et al*., 2003). The types of household products that may be found in greywater can contain pollutants such as Na, chlorides, and other salts, all of which may have an adverse effect on plant and soil health (Roesner *et al.*, 2006).

The amount of dissolved ions in greywater, known as its salinity, is measured using the EC value. Greywater that is intended for irrigation use should have a low EC value (< 1 300 µS/cm), as high EC can lead to salt-loading in the soil and an adverse effect on plants (Bakare *et al*., 2017). Certain plants are more tolerant of high salinity concentrations than others. Salts are absorbed from the soil through the roots and then travel through the plant to accumulate in the leaves. Deciduous plants are often more tolerant to greywater irrigation and high salt loads possibly because they drop their leaves once a year, which prevents an accumulation of toxins in the plant (Roesner *et al*., 2006).

It is highly recommended that soil irrigated with greywater be flushed regularly with freshwater to prevent the accumulation of organic matter and salts in the soil (Al-Hamaideh and Bino, 2010). If greywater is considered for use in irrigating edible plants, it is important to note the method of irrigation. Ideally the edible parts of food crops should not come into direct contact (i.e. should not be sprayed) with greywater, in case of pathogenic contamination, which can lead to human health issues (Finley *et al*., 2009). Greywater can be utilized directly, as long as the soil conditions and space is favourable for the disposal of untreated greywater. Trenches are dug and then filled with mulch, into which the greywater can be disposed. The mulch will filter out solids and other particles such as hair and lint, and the water percolates into the soil below (ESF, 2008).

2.4.5. Characteristics of greywater

While there are general characteristics that can be expected in greywater, such as increased alkalinity and high nutrient value, greywater composition is greatly dependent on its source (Carden *et al.,* 2007a). Household greywater may contain detergents, bleaches, surfactants, dyes, fragrances, and other chemicals that cause a change in greywater characteristics such as pH, EC, BOD and SS. The concentrations of these chemicals will vary depending on the number of people in a household, the products they use, their activities, and seasonal variations in water use and consumption (Roesner *et al.*, 2006). Birks and Hills (2007), have collated a comparison of general greywater characteristics from numerous studies (Table 3). There are a number of water quality characteristics that are considered when determining the suitability of greywater for various uses, and these characteristics are described below.

2.4.5.1. pH

The pH level of a sample will determine the availability of any chemical elements that may be present in the greywater such as aluminium (Al) and other metals (Carden *et al*., 2007a). Changes in soil pH, as a result of chemical additions, can affect soil microbial populations. Foliar damage and decreased crop yield, as well as damage to fruit can occur with direct contact with water of a very high or very low pH (DWAF, 1996b). Domestic greywater such as wastewater from the laundry, and bathroom basins and showers, generally has an elevated pH and alkalinity, and high concentrations of micronutrients such as boron (B) (Doughten, 2010). This type of greywater commonly contains a mixture of chemicals such as surfactants, bleaches, dyes, detergents, personal care products, and pharmaceuticals. However, it is often lower in macronutrients such as nitrogen (N), phosphorous (P), and potassium (K) in comparison to combined wastewater (Doughten, 2010), which includes toilet water. Greywater with a high pH i.e. alkaline conditions, will generally present with unavailable toxic metals (Carden *et al*., 2007a). A study by Bakare *et al.* (2017), showed that kitchen greywater generally has a low pH value when compared with laundry and bath greywater. This is possibly a result of the presence of food particles and oils, and the fact that greywater degrades faster in the anoxic conditions present in this source. The Target Water Quality Range (TWQR) for pH of irrigation water is between 6.5 and 8.4, where there is little effect on the soil pH, and no marked increase in the availability of toxins in the soil or decrease in nutrient availability (DWAF, 1996b).

Table 3. A comparison of the characteristics of different sources of greywater collected from bathroom sinks, baths, and showers ('light' greywater) (adapted from Birks and Hills, 2007).

Parameter	Rose *et al.*, 1990	Christova-Boal *et al.*, 1996	Harold and Ward, 1998	Surendran and Wheatley, 1998	Birks *et al.*, 2004; Smith *et al.*, 2001	Laine 2011
Greywater type*	B, S, W, L	B, S	B, S, W	B, S, W	W	B, S, W
BOD (mg/L)	-	76 - 200	33	216 – 252	5 - 142	129 - 155
COD (mg/L)	-	-	40	424 – 433	21 - 355	367 - 587
SS (mg/L)	-	48 - 120	-	40 – 76	7 - 102	58 - 153
Turbidity (NTU)	20 - 140	113	20	57	-	60 - 164
pH	5 - 7	6.4 - 8.1	-	7.7	-	7.3 - 7.5
Ammonia (NH_3) as N (mg/L)	0.15 - 3.2	< 0.1 - 15	1.1	0.5 - 1.6	-	-
Total P (mg/L)	4 - 35	0.11 - 1.8	-	1.6 - 45.5	-	0.3 - 0.4
Total coliforms (cfu/100 mL)	6.1×10^6	$500 - 2.4 \times 10^7$	-	$5 \times 10^4 – 6 \times 10^6$	$> 2.4 \times 10^3 - 10^6$	$6.4 \times 10^3 - 9.4 \times 10^3$
Faecal coliforms (cfu/100 mL)	$1.8 \times 10^4 - 7.9 \times 10^6$	$170 - 3.3 \times 10^3$	-	32 – 600	-	-
***E. coli* (cfu/100 mL)**	-	-	-	-	$0 - 2.4 \times 10^6$	$10 - 1.5 \times 10^3$

*B = bath; S = shower; W = washbasin; L = Laundry water.

2.4.5.2. Electrical conductivity (EC)

Electrical conductivity (EC) is used as a measure of the amount of dissolved salts in water, and the ability of water to conduct an electrical current (Carden *et al.,* 2007 b). The EC of water is generally used as a measure of total dissolved solids (TDS), which is the concentration of inorganic salts dissolved in the water, such as carbonate (CO_3), bicarbonate (HCO_3), chlorine (Cl), sulphate (SO_4), ammonia (NH_3), Na, K, calcium (Ca), and magnesium (Mg) (DWAF, 1996a). An analysis of the EC of household greywater by Bakare *et al*. (2017), showed that bath water generally has a lower EC value than kitchen and laundry greywater. This is perhaps due to the higher concentrations of detergents, which contain salts, in kitchen and laundry water. High EC often indicates high ion or inorganic salt concentrations in water, which can cause a decrease in crop yield, and a change in soil characteristics (Bakare *et al*., 2017). The TWQR for EC in irrigation water is 40 mS/m to ensure no negative effects of inorganic salts on crop yield or soil conditions (DWAF, 1996a).

2.4.5.3. Turbidity

Turbidity of water refers to its clarity and is affected by the quantity of SS, which is dependent on the nature and particle size of the suspended matter. Suspended solids (SS) can include clay particles, living organisms, decayed organic matter, and suspended mineral matter (DWAF, 1996a). The amount of soap present in kitchen greywater and its contamination with food particles will result in a high turbidity as a result of high SS (Bakare *et al*., 2017). High turbidity or SS can cause the clogging of irrigation systems and the formation of soil crusts, which can inhibit seedling emergence and soil infiltration. The TWQR for SS in irrigation water is 50 mg/L (DWAF, 1996a).

2.4.5.4. Chemical oxygen demand (COD)

Chemical oxygen demand (COD) is a measurement of the amount of oxygen that is required to oxidize organic material in water, and can be regarded as an indication of the pollution strength of greywater (Bakare *et al*., 2017). Kitchen greywater generally has a higher average COD value compared with laundry or bath greywater (Bakare *et al*., 2017). However, COD concentrations of greywater, whether it includes kitchen water or not, is generally relatively high (up to 580 mg/L in some examples) (Birks and Hill, 2007).

2.4.5.5. Biological oxygen demand (BOD)

The amount of organic compounds that are present in a sample of water and can be biologically oxidized is measured as the BOD of that sample (Bakare *et al*., 2017). Biological oxygen demand (BOD) concentrations are generally relatively high in greywater (up to 250 mg/L in some examples) (Birks and Hill, 2007).

2.4.5.6. Nitrogen (N)

Nitrogen (N) in greywater can be present as NO_3, or organic N and NH_3, and in grey- or wastewater, organic N is usually present in organic solids (Environmental Protection Agency (EPA), 1993). An excessive amount of N in water, in the form of NO_3, can cause concern as it is one of the main nutrients required by plants for growth. Thus, too much N in irrigation water can cause an increase in eutrophication in surface water bodies through run-off, as well as contamination of groundwater (DWAF, 1996a). Nitrogen (N) is generally present in greywater in smaller amounts (approximately 10 times lower) than in blackwater due to the exclusion of domestic sewage from greywater (Birks and Hill, 2007). The TWQR for N in irrigation water in terms of its effects on crop yield, surface water quality, and ground water contamination is 5 mg/L (DWAF, 1996a).

2.4.5.7. Phosphorous (P)

Greywater can contain higher concentrations of P than blackwater, usually as a result of the presence of detergents in washing powder (Birks and Hill, 2007). Softeners in detergents can contain polyphosphates which cause the solution to become alkaline and assist in effective cleaning. Phosphates (PO_4) can be indicative of pollution from sources such as sewerage, fertilizers, and detergents and act as an algal nutrient, causing eutrophication of surface water bodies (Carden *et al*., 2007a).

2.4.5.8. Pathogenic organisms

Greywater from laundry and kitchen use may contain microorganisms, and pathogenic organisms such as viruses, bacteria, protozoa and helminthes (Carden *et al*., 2007a). Common examples of pathogens that are associated with greywater include *E. coli, Salmonella* spp., *Shigella* spp., *Vibrio cholerae*, *Campylobacter* spp., and *Legionella* spp. (Roesner *et al.*, 2006). Indicator organisms, namely total and faecal coliforms, are used to measure the microbial characteristics of greywater and the presence of microorganisms (Doughten, 2010).

Total coliforms represent a broad bacterial group of microorganisms that can be found naturally in water, plants and soil; thus, they are generally not an accurate indicator of faecal contamination. Faecal coliforms, however, are total coliforms found specifically in the gut of warm-blooded animals and their presence in water will indicate faecal contamination (Roesner *et al.*, 2006). There is generally a high level of bacteria including pathogenic microorganisms present in untreated greywater (Birks and Hill, 2007), which are usually introduced into the water during showering, bathing and washing of anything that has been contaminated with faecal matter (Roesner *et al.*, 2006).

The risk of exposure to potentially pathogenic microorganisms is highest when untreated greywater is used in spray or furrow irrigation of crops or vegetables (Blumenthal *et al.,* 2000). Pathogenic coliforms can be harmful if counts in water exceed a dose of 10 - 1 000 counts/100 mL (DWAF, 1996a).

Untreated greywater also has the potential for a significant growth in total and faecal coliforms over 48 hours in storage (Roesner *et al.*, 2006), and can contain pathogenic microorganisms, which can increase the chance of viral infections in humans (Al-Jayyousi, 2003). The TWQR for faecal coliforms in irrigation water is one *E. coli* count/100 mL, where there is little to no chance that irrigation will lead to the spread of pathogenic microorganisms (DWAF, 1996a).

2.4.5.9. Oil and grease

Biological oil and grease (from animal fat or vegetable oil) can be introduced into greywater through the washing of dishes used in cooking, and is generally higher in kitchen greywater (Carden *et al.*, 2007a) than bath/shower or laundry greywater. The oil and grease component of greywater is hydrophobic, or water-repellent, and over a long period of time, soil irrigated with water high in oil and grease can exhibit a reduction in soil water movement (Travis *et al*., 2008). Oil and grease also has the ability to clog soil surfaces and cause smells (Carden *et al.*, 2007a) and can be found in concentrations of between 10 mg/L in bathroom greywater sources, and 200 mg/L in kitchen greywater sources (Travis, *et al.,* 2008). This component of greywater can be removed through the use of grease traps as part of the treatment process.

2.4.5.10. Boron (B)

While B is found naturally in the form of borates and borosilicate minerals, additional B even at very low concentrations can be toxic to plants and can result in lower crop yields or foliar damage (DWAF, 1996a). Boron (B) is found artificially in soaps, detergents, and antiseptic agents (Carden *et al.,* 2007a). A concentration of B in water used for irrigation of 0.5 - 1.0 μg/L can be toxic to certain landscape plants (Roesner *et al.*, 2006). Thus, the TWQR for B in irrigation water is 0.5 μg/L, which should prevent the toxic accumulation of B in irrigated plants (DWAF, 1996a).

2.4.5.11. Sodium (Na)

Soils that have been irrigated with water high in HCO_3 or CO_3 concentrations are often high in Na and thus show a relative increase in SAR (DWAF, 1996a). The Na in greywater is often a by-product of the presence of detergents. The SAR of a water sample will indicate the potential of the irrigation water to produce high concentrations of Na in the soil and is calculated using Ca, Mg, and Na concentrations (Carden *et al.,* 2007a). The SAR measurement also shows the potential of irrigated soil to become sodic i.e. high Na (DWAF, 1996a) and the value will increase with an increase in salt content or EC (Carden *et al*., 2007a). The TWQR for SAR as suggested by the South African Water Quality Guidelines for Irrigation (WQG/I) (DWAF, 1996) is 2.0 or less than 70 mg/L (Engelbrecht and Murphy, 2006), a level at which no Na toxicity will occur in plants, provided the soil is watered directly. Sodium (Na) toxicity can cause a reduction in soil permeability i.e. its infiltration rate and hydraulic permeability and an increase in hardsetting (the formation of crusts), as well as reduced crop yield and quality, especially in Na-sensitive plants (DWAF, 1996a).

2.4.5.12. Other toxins

There has been little research conducted on the presence of other toxins such as metals and other organic compounds in greywater; however, certain detergents, soaps, and personal hygiene products may contain certain harmful organic compounds that may be potentially toxic to plants (Carden *et al.,* 2007a). A study by Eriksson *et al*. (2010), which was done in Copenhagen, Denmark, showed that greywater sludge contained concentrations of metals such as cadmium (Cd), nickel (Ni), and lead (Pb) at concentrations greater than that of the Danish quality criteria for agricultural compost. This may indicate the need to test for metals in greywater and potentially implement a treatment process to remove metals and other toxins if the greywater is intended for use in irrigation, specifically for vegetable gardens.

2.4.6. Pollution potential of greywater

It has been suggested that greywater has a higher pollution potential than blackwater (i.e. sewerage), mainly due to its high rate of decomposition. As a result of the high level of decay in greywater pollutants, greywater directly discharged into surface water bodies has a much more immediate effect on its water quality (Carden *et al.,* 2007a). Kitchen greywater generally has a higher BOD and COD level than laundry or bath greywater, which suggests a higher concentration of organic compounds and greater potential for pollution (Bakare *et al*., 2017). However, there has been no significant and causative link demonstrated, as yet, between the use of greywater and the incidence of illness in a household using greywater. Nonetheless, operating principles must be put into place to prevent the potential transmission of illnesses through the re-use of greywater (Doughten, 2010).

2.4.7. Greywater treatment

The variation in greywater composition from source to source provides some difficulty in successfully treating it (Al-Jayyousi, 2003). In some circumstances, greywater can have higher concentrations of pollutants such as B and surfactants than blackwater, and may be of similar quality to blackwater in terms of BOD and faecal coliforms (Gross *et al*., 2005). When determining a suitable greywater treatment process, it is important to consider whether it is cost-effective, efficient, and sustainable. For example, in small rural communities, or even suburban households, a simple low-tech system that is low-cost and effective may be most suitable (Frazer-Williams, 2007). Domestic greywater treatment should be sustainable and affordable, with low capital requirements and maintenance costs, which make treatment processes such as CW a viable small-scale option (Avery *et al.,* 2007). It is generally recommended that greywater with a high polluting strength such as kitchen greywater, undergoes treatment before use; again, this can be done using low cost methods such as CW (Bakare *et al*., 2017).

2.5. Wetlands

Wetlands are described by the Ramsar Convention Secretariat (2013) as areas with natural or artificial water, permanent or temporary water, static or flowing water, fresh, brackish, or salt water, and areas of marsh, fen or peatland. The definition of wetlands may incorporate the areas adjacent to them, such as riparian and coastal zones, as well as islands and bodies of marine water that are deeper than six metres at low tide that lie within the wetlands. This includes areas such as rivers, lakes, peatlands, marshes, and floodplains, as well as mangroves, saltmarshes, and seagrass beds. The Ramsar definition also recognizes coral reefs and marine habitats with a depth at low tide of six metres and less as wetlands, and wastewater treatment ponds and reservoirs as artificial wetlands (The Ramsar Sites Criteria Brochure, *n.d*). Wetlands will occur in areas where the water table is at or near the surface of the land, where the land is covered by shallow water, or where the primary factor controlling the environment and associated flora and fauna is water.

There are six Ramsar sites in SA, namely:

- Nylsvley Nature Reserve;
- Verloren Valei Nature Reserve;
- Blesbokspruit;
- Natal Drakensberg Park;
- Seekoeivlei Nature Reserve; and
- Lake Sibaya.

2.5.1. Global wetland importance

Ramsar wetland sites are recognized as being of significant value for the country/countries in which they are located, as well as for humanity overall, and are designated according to the following nine criteria (The Ramsar Sites Criteria Brochure, *n.d.*):

- A wetland should be considered internationally important if it contains a representative, rare, or unique example of a natural or near-natural wetland type found within the appropriate biogeographic region;
- A wetland should be considered internationally important if it supports vulnerable, endangered, or critically endangered species or threatened ecological communities;
- A wetland should be considered internationally important if it supports populations of plant and/or animal species important for maintaining the biological diversity of a particular biogeographic region;
- A wetland should be considered internationally important if it supports plant and/or animal species at a critical stage in their life cycles, or provides refuge during adverse conditions;
- A wetland should be considered internationally important if it regularly supports 20 000 or more water birds;
- A wetland should be considered internationally important if it regularly supports 1% of the individuals in a population of one species or subspecies of water bird;
- A wetland should be considered internationally important if it supports a significant proportion of indigenous fish subspecies, species or families, life-history stages, specie interactions and/or populations that are representative of wetland benefits and/or values and thereby contributes to global biological diversity;

- A wetland should be considered internationally important if it is an important source of food for fishes, spawning ground, and nursery and/or migration paths on which fish stocks, either within the wetland or elsewhere, depend; and
- A wetland should be considered internationally important if it regularly supports 1% of the individuals in a population of one species or subspecies of wetland-dependant non-avian animal species.

Ramsar also uses a classification system for wetland types, which is used to determine the main wetland habitat type represented at a site. These are divided into three main groups namely, marine/coastal wetlands, inland wetlands, and human-made wetlands (Ramsar Convention Secretariat, 2013).

2.5.2. Importance of wetlands in South Africa (SA)

The NWA describes wetlands as "*land that is transitional between terrestrial and aquatic systems, and where the land may be covered with shallow water periodically, where the water table is at or near the surface, and where the land typically supports vegetation that is adapted to life in saturated soils*".

Wetlands provide a variety of essential ecosystem functions, such as flood control, nutrient cycling, provision of food and water, and sites for education and cultural activities. Wetlands are valuable mainly due to their ability to process water and regulate runoff, which is essential for our country's economy, agriculture, industry, and mining and is very important in a dry country such as SA (DWAF, 2005). Wetland ecosystems are sites of intense biogeochemical activities that contribute to the improvement of water quality by filtering and removing toxins and pollutants from water (Van Vuuren, 2014). Wetlands are known to be very effective at sequestering pollutants such as metals and remediating contaminated waters (Humphries *et al*., 2017).

Wetlands provide a number of regulating and supporting benefits that are essential to a developing country such as SA, including flood attenuation, stream regulation, sediment trapping, PO_4 assimilation, NO_3 assimilation, toxicant assimilation, erosion control, and carbon storage (Kotze *et al*., 2007). Wetlands also support the maintenance of biodiversity and provide direct benefits such as the provision of water for human use, the provision of harvestable resources, the provision of cultivated foods, cultural heritage, tourism and recreation, and education and research (Kotze *et al*., 2007).

Nationally, wetland loss is thought to be high, with certain wetland types suffering more severe loss than others, such as rare dolomitic wetlands (Kotze *et al.,* 2007). The main drivers behind wetland degradation in SA are the drainage of wetlands for agriculture, poorly managed grazing and burning, the presence of invasive alien plants in wetlands, urban development, mining, and pollution. This has led to the destruction of more than 50% of the country's wetlands (DWAF, 2005).

2.6. Constructed wetlands (CW)

The official concept of CW for use in wastewater treatment was first developed in Germany in the 1960s (Bean and Yang, 2009). The theory of CW assumes the development of simple, manageable, cost-effective wastewater treatment systems that mimic natural wetlands in the purification and treatment of wastewater (ESF, 2008). Constructed wetlands (CW) have been designed and engineered to utilize natural processes such as wetland vegetation, soils, and associated microbial assemblages to treat and process wastewater within a controlled environment (Vymazal, 2010). Constructed wetlands (CW) are different from natural wetlands in that their size remains constant and water in the system should not come into contact with groundwater (Madungwe and Sakuringwa, 2007).

The EPA defines a CW as a wetland that is designed and constructed specifically for the purpose of controlling pollution and waste management in an area other than an existing natural wetland (EPA, 1993). Constructed wetlands utilize wetland plants, soil, and microorganisms to function and process water as would a natural wetland (EFS, 2008). Constructed wetlands can also be used for the treatment of landfill leachate, feed lot and agricultural runoff, acid mine drainage, stormwater runoff, and combined sewer overflows (EPA, 1993). The benefits of CW include lower construction and maintenance costs, aesthetically pleasing designs, and a reduction in odour as compared to more traditional wastewater treatment facilities (Bean and Yang, 2009). Constructed wetlands are also effective at treating greywater and are a low-cost alternative especially for small communities, suburban households, or rural villages, as they have low running costs, can be maintained by low-skilled people, have little to no energy requirements, and are perceived as natural systems (Frazer-Williams, 2007). These systems are also beneficial in the ecological sense and in the garden (Hyun *et al*., 2016) as they increase biodiversity, and attract local wildlife into urban gardens and landscapes.

Biological wastewater treatment methods can be divided into two categories based on the conditions within which the treatment takes place, namely, aerobic (in the presence of oxygen) and anaerobic (in the absence of oxygen). Constructed wetlands usually fall within the aerobic category and can be run and maintained by unskilled operators (Ghaitidak and Yadav, 2013). Generally, CW systems are most appropriate for use on small amounts of wastewater as they require relatively large areas for construction, and long periods of retention time to treat the water to satisfactory levels (Hyun *et al.*, 2016).

Household greywater can be treated sustainably, efficiently, and biologically with organic-based systems such as CW and evapotranspiration beds (Carden *et al.*, 2007a). When utilizing CW for treatment of greywater, it is necessary to implement a pre-treatment process that removes hair, lint, oil, food particles, fat, and other solids from the water before it moves through the system (ESF, 2008). Planting a variety of vegetation types in a CW can increase the diversity of microbial populations supported by the plants' roots. This could then facilitate a more effective removal of pollutants from the greywater (Avery *et al*., 2007; Hyun *et al*., 2016). Hyun *et al*. (2016), found that aquatic plants did not contribute to the oxygen concentrations required for efficient treatment of wastewater in an aerobic system, and added aeration was required to oxygenate the system. Aeration of the system at the point of the wastewater inlet also assists in the removal of N, COD, and organic matter, and prevents clogging. The addition of plants to a CW system mainly contributes to green space and aesthetics (Hyun et *al.*, 2016). However, Zhang *et al.* (2014), suggested that seasonal variations in plant growth and temperature have a significant effect on the ability of CW systems to remove contaminants from wastewater; notably, the effectiveness of the system decreases in colder temperatures as a result of a reduction in biotic activity.

2.6.1. Types of constructed wetlands (CW)

There are three categories into which CW can be divided, namely, free water surface (FWS) CW, SSF CW, and hybrid CW (Zhang *et al.*, 2014). Constructed wetlands are typically less than a metre deep and are planted with selected aquatic plants within porous media or engineered soil (Maupin, 2011). These systems can be designed to provide a variety of purposes in addition to greywater treatment, such as flood control, carbon sequestration, or wildlife habitat (Vymazal, 2010).

2.6.1.1. Free water surface (FWS) wetland

The FWS design (Figure 2) consists of a horizontal flow path, with surface water that is exposed to the environment (EPA, 1993). It is also known as a surface flow (SF) system (Frazer-Williams, 2007). An arrangement of channels or basins is lined to prevent seepage, and these channels contain soil and emergent vegetation with water at a shallow depth that flows through the system (EPA, 1993). The SF system design ensures that a shallow basin is filled with soil or other suitable media and there is a controlled water level to maintain the submergence of sediment, leaf litter and soil (Frazer-Williams, 2007). The water layer near the surface is aerobic, while the substrate and deeper water layers are usually anaerobic (Zhang *et al.,* 2014). Water flows directly over the surface of the gravel layer, and while this design is less complex and more cost effective to install (Bean and Yang, 2009), there is a greater risk of odour, water-borne parasites, and human contact. The structure of the SF system ensures a permanent horizontal flow of water at a stable depth and its landscape design mimics a natural wetland system (Frazer-Williams, 2007) in both appearance and function (Jokerst *et al.,* 2009). Surface flow (SF) wetlands also support a more diverse wildlife habitat (Bean and Yang, 2009).

While SF CW have found to be moderately effective in the removal of NO_3, ammonium (NH_4), and total N, as well as P, these systems are inefficient in the removal of total SS, BOD, and COD from wastewater (Zhang *et al.,* 2014).

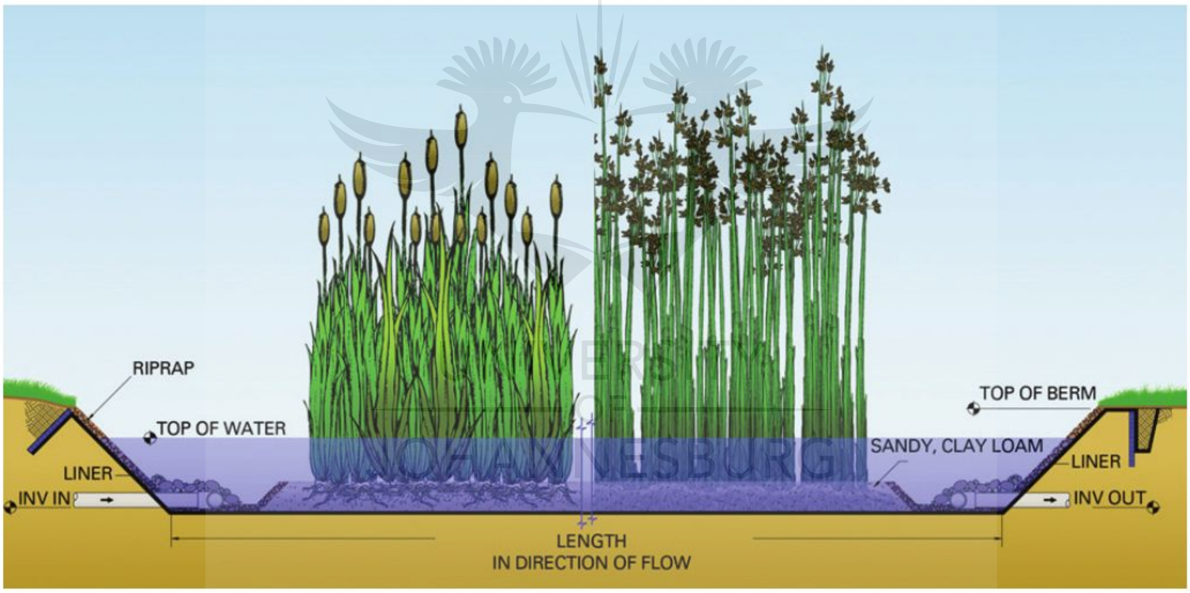

Figure 2. Diagrammatic interpretation of a SF or FWS wetland design (Bean and Yang, 2009).

2.6.1.2. Sub-surface flow (SSF) wetland

Sub-surface flow (SSF) wetlands, initially described as the root-zone method (RZM) by Frazer-Williams (2007), are made up of a basin or channel with a barrier to prevent seepage, and a bed of porous media such as rock or gravel (Figure 3). The type of media used depends on the required hydraulic EC and surface area (Table 4). For example, large gravel stones have a high EC, but a low wetted surface area per unit volume, while small stone particles encourage surface flow but have a low EC (Frazer-Williams, 2007). Emergent vegetation is planted into the media and the horizontal flow path of the water remains sub-surface (EPA, 1993). Liners of material such as high, medium, or low density polyethylene, bentonite, or puddle clay are used to prevent leaks, or seepage of water into the ground, which may cause groundwater pollution (Frazer-Williams, 2007). The design ensures no flow of water on the surface, which makes them ideal for use near housing or office buildings as there is less risk of human contact, odour, or mosquitoes (Bean and Yang, 2009). Poor oxygenation may cause odour problems in SSF systems, which can then be ameliorated by increasing aeration, light and temperature in the system (Ilemobade *et al*., 2012).

The main requirement for SSF design is to maintain sub-surface water flow, and this requires the prevention of clogging of the media, and a sufficient hydraulic gradient or EC of media, aspect ratio (depth of bed divided by length of flow path), and bed slope (percentage slope) to encourage water flow (EPA, 1993). Sub-surface flow (SSF) wetlands have been found to be very effective at the removal of organic matter, SS, and nutrients such as NO_3 and PO_4 (Ilemobade *et al*., 2012). The efficiency of an SSF wetland is expected to increase over time, and the treatment process may not be as effective in a very young system (Laaffat *et al*., 2015).

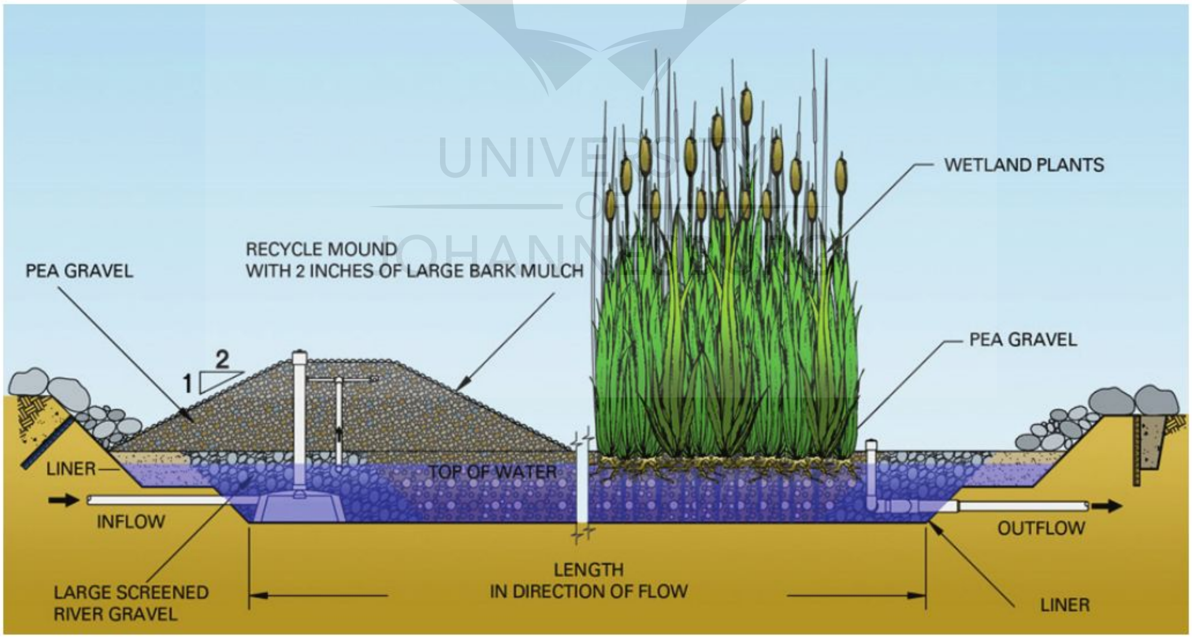

Figure 3. Diagrammatic interpretation of a SSF wetland design (Bean and Yang, 2009).

Aquatic plants are added to SSF systems to enhance nutrient removal from wastewater (Ling *et al*., 2009) and have been shown to significantly reduce contaminants in treated water (Zhang *et al*., 2014). Vegetation with deeper root penetration is able to treat greywater more effectively, with roots at 0.8 m (e.g. *Scirpus* spp.) reducing BOD by 95.8%, SS by

92.9%, and NH_3 by 92%. Roots at 0.6 m (such as *Phragmites* spp.) can reduce BOD by 81.3%, SS by 85.9%, and NH_3 by 80%, while SSF beds with no vegetation reduce BOD by 69.5%, SS by 89.5%, and NH_3 by 12%, (EPA, 1993).

Table 4. Size, porosity, and hydraulic EC of media of various sizes, for use in a SSF wetland design (EPA, 1993).

Media type	Effective size (D_{10} mm)	Porosity (%)	Hydraulic EC (m^3/m^2/day)
Coarse sand	2	32	1 000
Gravelly sand	8	35	5 000
Fine gravel	16	38	7 500
Medium gravel	32	40	10 000
Coarse rock	128	45	100 000

In addition, it has been shown that ornamental plants grown in SSF wetland systems may act as nutrient storage facilities, as they show higher P concentrations and weight than those not grown in wastewater (Ling *et al*., 2009). Plants that are grown in CW systems, specifically reeds such as *Phragmites* spp., can be harvested when necessary and further utilised for biomass fuel; housing material; high-strength fibre; pulp and paper production; livestock forage; and a soil conditioner (Masi, 2009). Zhang *et al*. (2014), suggested planting a variety of different macrophytic species in a CW to allow for different seasonal growth patterns, and root characteristics that enhance the performance of the system.

2.6.1.3. Hybrid systems

Hybrid systems (Figure 4) consist of a combination of SSF and FWS wetland types that are staged in series to effectively combine the advantages of each system. Hybrid systems are generally more effective at removing SS, COD, NH_4 and total N than single-type systems working alone (Zhang *et al*., 2014).

2.6.2. Uses

Constructed wetlands (CW) are used worldwide for the treatment and processing of wastewater effluent and can provide efficient, on-site solutions to greywater discharge (Jokerst *et al.,* 2009). Treatment wetlands, as they are alternatively known as, have the capability to reduce wastewater components such as BOD, COD, and SS by up to 83%, while only removing nutrients, such as NO_3 and PO_4 by up to 45% (Frazer-Williams, 2007). The inability of these systems to remove high concentrations of nutrients is possibly due to the fact that they cannot present both anoxic and oxic conditions simultaneously, which are required for denitrification and nitrification consecutively (Frazer-Williams, 2007). There are a number of advantages to the utilisation of CW systems for treatment of domestic greywater (ESF, 2008):

- No external energy required (no pumping) due to gravity flow;
- Hair, soap, residues etc. will be retained (at the point of greywater application) by the mulch material;
- Use of locally available organics (e.g. rice husk etc.) as mulch material; and
- Greywater gardens can be redesigned easily by simply ploughing the soil (organic material will be mixed with the soil).

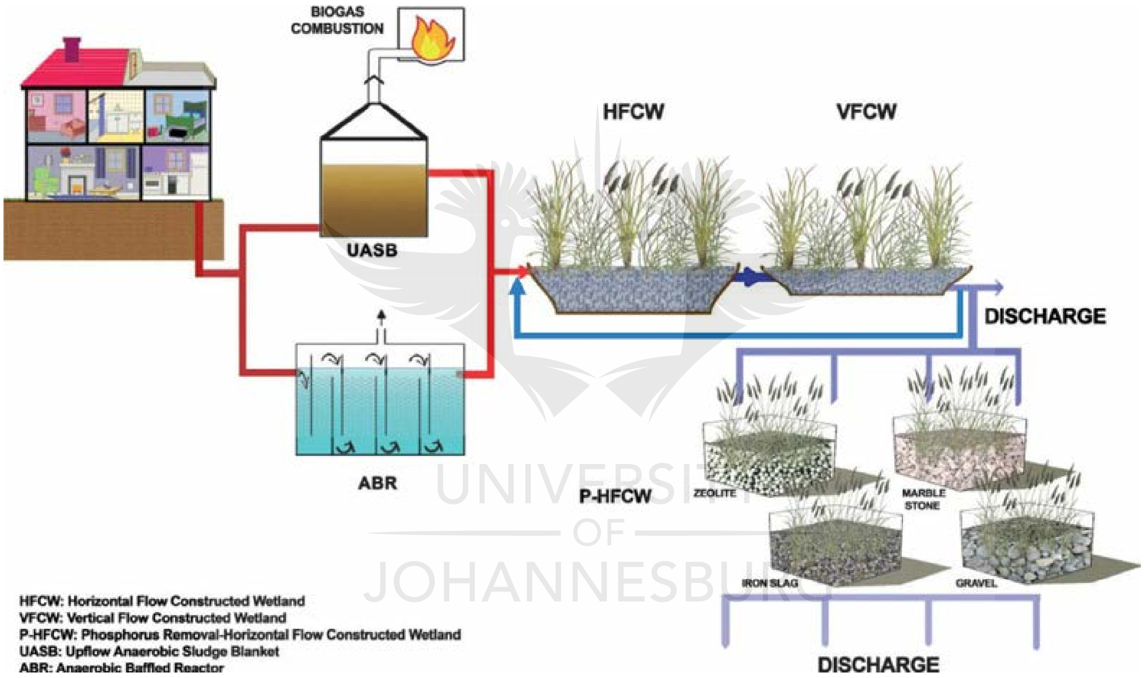

Figure 4. Diagrammatic interpretation of a hybrid wetland design (Ayaz et al., 2012).

2.6.3. Treatment of household greywater

Constructed wetlands (CW) can be used to treat greywater in single households since these wetlands are quite flexible systems (Hoffman *et al*., 2011). Bakare *et al*. (2017), recommended the use of natural treatment systems such as CW to treat greywater, mainly due to low cost and maintenance requirements. Constructed wetlands (CW) have been shown to provide an efficient onsite treatment process for greywater, and can significantly reduce greywater contaminants such as pathogens, BOD, solids, N and P (Jokerst *et al.*, 2009). These artificial wetlands are the most common systems used for the treatment of decentralized greywater (Paulo *et al.*, 2013). Constructed wetlands (CW) with elements of biological treatment can remove about 90% of organic matter, 90-100% of SS, 90-99% of BOD, 100% of COD, 87-100% of PO_4^3, and 40-100% of N from domestic greywater (Rodda *et al.,* 2010). Rodda *et al.* (2010) also suggested that artificial wetlands can be used to further treat greywater before discharge or disposal into stormwater systems.

Constructed wetlands (CW) are considered affordable, operable, reliable, and can yield consistent effluent quality, as long as these systems are consistently and properly maintained (Maupin, 2011). Paulo *et al.* (2013), have shown that CW are a cost-effective and efficient ecological alternative to the treatment and management of greywater at a household level.

The sand or gravel media and aquatic plants used in CW are responsible for retaining and removing certain pollutants found in greywater (Wurochekke *et al.,* 2015). Gravel is a more effective media for treatment of wastewater as it is not as susceptible to clogging and surface overflow as sand or soil substrates (Frazer-Williams, 2007). Gross *et al.* (2007), set out to design a treatment system for greywater that is low-tech, easy to maintain and economically sound, and which would treat greywater so that it is safe to use for landscape irrigation in households and communities. The vertical flow system consisted of containers placed on top of one another to act as filters and reservoirs through which the greywater flowed. This system removed enough pollutants to ensure the treated water had no negative impact on the plants or soil it was used to irrigate. In general, CW systems have been found to effectively remove up to 98% of SS, more than 99% of BOD, up to 82% COD, up to 82% total N, and up to 95% oil and grease (Ghaitidak and Yadav, 2013). Jokerst *et al*. (2009), showed that CW are also able to significantly reduce pathogenic microorganisms, and nutrients such as PO_4.

2.6.3.1. Biofilms

In many greywater treatment systems, including CW, biofilms containing diverse microbial communities are present that degrade various constituents that are present in greywater, such as surfactants (Roesner *et al.*, 2006). In CW with gravel or stone media, biofilms form around these hard surfaces, as well as around the surface of aquatic plants. These biofilms are responsible for metabolizing contaminants and nutrients in the water, as well as oxygen removal, and perform processes that are essential for the successful functioning of any wetland system (Mthembu *et al*., 2013).

2.6.3.2. Biological oxygen demand (BOD)

Constructed wetland (CW) systems such as the FWS and SF systems may show residual BOD, as decaying plant matter cause the production of additional BOD within the system that is not of wastewater origin (EPA, 1993). The microbial growth on the surface of media such as gravel and stones, as well as on the roots of plants removes soluble BOD from greywater, while BOD is physically removed with the settling of particulate matter in the spaces between the gravel and stone media (EPA, 1993).

2.6.3.3. Total suspended solids (SS)

The removal of SS is very effective in the SF system, where removal occurs within the first few metres from the inlet zone (EPA, 1993).

2.6.3.4. Nitrogen (N)

Non-ionized NH_3 is toxic to fish and other aquatic animals and its removal through CW is essential (EPA, 1993). Microbiological activity in CW can result in the removal of organic N through the denitrification process, and its conversion to NH_3; thereafter, the emergent plants remove NH_3 from the treated water. However, the process of denitrification relies on the presence of oxygen and will not occur in an anaerobic environment (EPA, 1993). Media depth in most CW occurs to approximately 0.6 m below the surface, while plant roots only penetrate to a maximum of 0.3 m depth in these systems. This may affect the availability of oxygen for the denitrification process (EPA, 1993).

2.6.3.5. Phosphorous (P)

The use of gravel media in CW is not effective in the removal of P from greywater as contact time between the water and media is limited. Introducing finer media such as sand to the system may increase P removal, but it may also slow down the movement of water through the system (EPA, 1993). Ghaitidak and Yadav (2013), suggested an increase in the volume capacity of the system may assist in increasing the removal of P in CW systems. Once again, the type of media used in the CW will determine the ability of the system to remove P, as its removal is reliant on both abiotic and biotic processes (Frazer-Williams, 2007).

2.6.3.6. Faecal coliform

Surface flow (SF) systems generally do not reduce faecal coliform counts to a level that satisfies general standards and final disinfection may be required (EPA, 1993). Ghaitidak and Yadav (2013), suggested post-treatment of CW effluent to remove pathogens and microorganisms to meet re-use standards. A combination of physical, chemical, and biological processes within the CW system is required for the effective removal of microbial indicators, such as faecal coliforms (Frazer-Williams, 2007).

2.6.4. Limitations to using constructed wetlands (CW) for greywater treatment

Liu *et al*. (2015), outlined a number of potential limitations to the use of CW for treatment of greywater, namely:

- Clogging of substrate when treating effluent high in organics and SS;
- Inability to efficiently remove N from wastewater;
- Inability to effectively remove certain recalcitrant pollutants and heavy metals from wastewater; and
- Inability to treat water to the required standards of re-use.

In addition, the use of CW for the treatment of greywater is not feasible in non-sewered, high-density settlements due to the space requirements and the potential for human and environmental health issues is high. In areas such as these the focus should be on the safe disposal of greywater instead (Carden *et al.,* 2007a). Paulo *et al*. (2013), recommended the monthly maintenance and cleaning of the system's grease trap to prevent clogging of the system and suggest that changing food preparation habits in the kitchen may reduce the incidence of clogging as a result of oil and grease.

There are a number of disadvantages in the use of CW for treatment of greywater at a household domestic level, as described by EFS (2008). For example, CW are unsuitable for densely populated areas with high greywater production if space for establishing greywater gardens is limited; and plants have to be taken care of and mulch has to be replaced (ESF, 2008).

2.7. Case study 1

Avery *et al.*, (2007), compared the efficiency of three different types of CW to treat low organic strength domestic greywater, with the intention to re-use the treated greywater. The study was conducted at Cranfield University in the United Kingdom (UK). Two of the designs were SSF reed beds, one vertical flow (SSFVF) and one horizontal flow (SSFHF). The third wetland was a new and innovative design (Green Roof Water Recycling System - GROW) that incorporated the use of aerated troughs and a tiered wooden framework to circulate the water through the specially-designed light-weight expanded clay media. The media was planted with a selection of garden plants and herbs. A number of water quality parameters were monitored to test the treatment efficiency of each CW, including BOD, COD, SS, turbidity, pH, dissolved oxygen (DO), NO_3, PO_4, and total coliforms. Rainfall was physically excluded from the treatment systems with reinforced membrane.

Results from this study (Table 5) showed that each system significantly reduced the amount of BOD in the greywater to authority standards, with no significant difference between the treatment efficiency of the wetlands. Similarly, COD reduction was significant before and after treatment for all wetlands; however the GROW system showed a slightly higher rate of COD removal than the SSFVF or SSFHF systems. The GROW system effectively reduced turbidity after treatment, while the SSFHF system actually caused an increase in treated effluent turbidity. While pH was significantly reduced for both SSF systems, the GROW system did not show a significant effect on the pH of the influent. The concentrations of NO_3, NH_3, and PO_4 in the greywater influent were as low as to have no negative implications for re-use; this is a result of the dilution of the greywater at the source. Most importantly, each system significantly reduced the amount of indicator organisms i.e. coliforms, before and after treatment. The results of this case study show that CW can successfully be used as low-cost, effective treatment systems for domestic greywater with the intention to re-use the greywater.

2.8. Case study 2

This case study refers to a study conducted by Lakay (2014) on the use of CW for the treatment of domestic wastewater (black and greywater) in the Western Cape, SA. Research was conducted on the efficiency of treatment of three *in-situ* CW, at three separate sites. The wetlands had previously been constructed to treat domestic wastewater from two farms and an estate, and so were established sites. The treated effluent was released into streams, culverts, or vleis at each site. Parameters that were investigated included NH_3, NO_3, orthophosphates, *E. coli* (as an indicator organism for faecal pathogenic coliforms), TDS, temperature, and pH.

The CW system at the first site was implemented in 2009 and served one household of 6-15 people in a secure estate in Noordhoek (Table 6). The system was designed to treat between 2 000 – 4 000 litres of domestic wastewater per day (this includes black and greywater) and had a surface area of 100 m^2. The second site was at the Wolwedans wine farm in Stellenbosch (Table 7) that treated wastewater from five households, an office, and three storerooms. It was implemented in 2007. The system was designed to treat between 1 100 litres and 3 300 litres of wastewater per day, and had a surface area of approximately 110 m^2. The third site was a fruit and wine farm, Babylonstoren Farm, in Simondium (Table 8), which treated the domestic wastewater produced by 25 employee residences and 12 guest houses. It was constructed in 2009 and was approximately 140m^2 in size. The system was designed to treat up to 50 000 litres of wastewater a day. This included sewage water and wastewater from the wine cellar. All wetlands were lined, either with clay or plastic, and were planted with a variety of aquatic plant species.

Results from this study (Table 6, 7, and 8) indicated that overall for three *in-situ* CW systems, the removal of pollutants from domestic wastewater, which included toilet water, was inefficient. It is possible that the systems were poorly designed and had short retention times that did not allow the water to be present in the system for long enough. Problems with lack of maintenance and vegetation growth at each site could also contribute to the poor performance of the systems. Lakay (2014), suggests that CW systems of this kind require specific management plans for different seasons.

There are a wide range of greywater treatment technologies available that allow the restoration and maintenance of the chemical and physical quality of greywater (Wurochekke *et al*., 2015). When reusing greywater for domestic applications, it is necessary to determine the chemical, physical and micro-organic components of the water to ensure it is used in a safe and sustainable manner (Erikkson *et al*., 2002). While greywater may in certain circumstances pose a threat to human health, the positives of the re-use of wastewater in a world where freshwater supplies are highly limited, far outweigh the negatives, as long as the correct precautions are taken (Finley *et al*., 2009). It is essential that SA, as a water-constrained country, focuses on conserving, managing, and expanding its limited water resources effectively to prevent a serious future water crisis (Turton, 2015). It is anticipated that this research will highlight the treatment efficiency of greywater by CW, so that treated greywater can be re-used for irrigation in residential gardens. Through the implementation of small-scale CW in a domestic setting, residents will decrease their demand on potable water supply and assist in conserving the country's water resources.

Table 5. Results of treatment of domestic greywater using three CW systems (adapted from Avery et al., 2007).

Parameter	**Sample type**	**Period 1 sampling event**			
		Mean ± SEM (n)	Removal efficiency (%)	ANOVA	
				F-value	*P*
BOD ($mg.dm^{-3}$)	Influent	18.1 ± 3.7	NA	311.6	<0.001
	HF effluent	3.1 ± 1.6	83.1		
	VF effluent	2.1 ± 1.6	88.2		
	GROW effluent	2.9 ± 1.6	84.0		
COD ($mg.dm^{-3}$)	Influent	85.0 ± 13.4	NA	104.8	<0.001
	HF effluent	54.7 ± 8.6	35.5		
	VF effluent	46.3 ± 11.3	45.5		
	GROW effluent	35.2 ± 8.7	58.6		
Turbidity (NTU)	Influent	27.9 ± 9.2	NA		
	HF effluent	42.2 ± 9.1	-51.3		
	VF effluent	16.3 ± 1.4	41.5		
	GROW effluent	1.9 ± 0.4	93.3		
Total coliforms (log_{10} CFU/100 cm^3)	Influent	5.0 ± 0.3	NA	261.8	<0.001
	HF effluent	2.3 ± 0.2	2.7		
	VF effluent	1.1 ± 0.1	4.0		
	GROW effluent	2.9 ± 0.2	2.1		

Table 5 continued.

pH	Influent	7.1 ± 0.1	NA	43.2	<0.001
	HF effluent	7.0 ± 0.1	NA		
	VF effluent	6.8 ± 0.0	NA		
	GROW effluent	7.5 ± 0.1	NA		
SS ($mg.dm^{-3}$)	Influent	36.6 ± 16.9	NA	78.8	<0.001
	HF effluent	16.2 ± 4.1	55.8		
	VF effluent	3.8 ± 1.0	89.7		
	GROW effluent	4.1 ± 1.4	88.9		
NO_3 ($mg.dm^{-3}$)	Influent	2.3	NA	5.6	0.002
	HF effluent	2.6	-		
	VF effluent	4.2	-		
	GROW effluent	2.3	-		
PO_4 ($mg.dm^{-3}$)	Influent	0.6	NA	22.7	<0.001
	HF effluent	0.2	-		
	VF effluent	0.1	-		
	GROW effluent	0.2	-		
NH_3 ($mg.dm^{-3}$)	Influent	0.9	NA	7.13	<0.001
	HF effluent	0.3	-		
	VF effluent	0.2	-		
	GROW effluent	0.1	-		

Table 6. Results of treatment of domestic wastewater using CW systems at the De Goede Hoop, Noordhoek site (adapted from Lakay, 2014).

Parameter	Sample type	Concentration	Removal efficiency (%)
NH_3 (mg/L)	Influent	30.37	NA
	Effluent	1.34	96
NO_3 (mg/L)	Influent	6.08	NA
	Effluent	14.05	-131
NO_2 (mg/L)	Influent	0.05	NA
	Effluent	0.08	-60
PO_4 (mg/L)	Influent	30.78	NA
	Effluent	29.61	3.8
E. coli **(CFU/100 mL)**	Influent	489 714	NA
	Effluent	74 786	85

Table 7. Results of treatment of domestic wastewater using CW systems at the Wolwedans Farm, Stellenbosch site (adapted from Lakay, 2014).

Parameter	Sample type	Concentration	Removal efficiency (%)
NH_3 (mg/L)	Influent	63.14	NA
	Effluent	41.07	35
NO_3 (mg/L)	Influent	14.28	NA
	Effluent	22.01	-54
NO_2 (mg/L)	Influent	2.09	NA
	Effluent	1.81	13
PO_4 (mg/L)	Influent	35.44	NA
	Effluent	28.21	20
E. coli **(CFU/100 mL)**	Influent	739 833	NA
	Effluent	691 075	39

Table 8. Results of treatment of domestic wastewater using CW systems at the Babylonstoren Farm, Simondium site (adapted from Lakay, 2014).

Parameter	Sample type	Concentration	Removal efficiency (%)
NH_3 (mg/L)	Influent	5	NA
	Effluent	10.45	-109
NO_3 (mg/L)	Influent	8.18	NA
	Effluent	5.78	29
NO_2 (mg/L)	Influent	0.09	NA
	Effluent	0.13	-44
PO_4 (mg/L)	Influent	20.72	NA
	Effluent	19.23	7
***E. coli* (CFU/100 mL)**	Influent	1 213 333	NA
	Effluent	426 667	65

Chapter 3: Materials and methods

Sites were selected that were in close vicinity to greywater sources, as well as in areas with a suitable gradient to accommodate the design of the CW. The design of the wetlands, specifically plant choice, was in line with the Highveld's climatic requirements.

3.1. Study area

The study site is located on Rand Water property, at the Environmental Management Services Department offices. These offices are based on a plot in the south of Johannesburg, adjacent to the town of Alberton, Gauteng.

3.1.1. Topography

The site is located approximately 500 m from the Klip River (Figure 5). The Klip River finds its source in Roodekrans on the West Rand and is a tributary of the Vaal River (Chihomvu *et al.,* 2014). The Klip River is approximately 100 km in length and its overall health is classified, according to the National Freshwater Ecosystem Priority Areas (NFEPA) system, as Class E-F. This means the system as a whole is '*seriously modified to critically/extremely modified*', with an almost complete loss of natural habitat and biota and a decrease in basic ecosystem functions to a point where changes may be irreversible (Driver *et al*., 2011). The Klip River has become heavily polluted, largely due to the impact of industrial activities such as mining (Chihomvu *et al*., 2015). The river is situated in Ecoregion 11 according to DWAF's ecoregional classification of rivers. Ecoregion 11 is defined as the Highveld (Table 9) (Kleynhans *et al.,* 2005). Many large rivers such as the Vet River, Modder River, Riet River, Vaal River, Olifants River, Steelpoort River, Marico River, Crocodile River, and the Great Usutu River, have their origins in the Highveld Ecoregion, which is determined by a moderate to low relief and various grassland types (Kleynhans *et al.,* 2005).

The Klip River also falls within a natural wetland, which is described as a Dry Highveld Grassland Group 5: channelled valley-bottom wetland (SANBI, 2018). Valley-bottom wetlands occur in valley bottoms and remain wetter for longer than seeps; channelled systems show clearly defined stream channels (Ollis *et al.,* 2013). The Dry Highveld Grassland ecosystem is found at an altitude of 1 300 – 1 600 masl (metres above sea-level). It is characterised by dominant semi-arid sweetveld that is drought-tolerant and is interspersed by shrublands on rocky koppies and slopes (SANBI, 2013). The topography is mostly flat to undulating, with the occasional outcropping of rocky ridges, and mountains, and rivers (SANBI, 2013).

Table 9. Characteristics of the Highveld Ecoregion (adapted from Kleynhans et al., 2005).

Main characteristics	Highveld Ecoregion
Terrain morphology	Plains, with low to moderate relief.
Vegetation types	Rocky Highveld Grassland; Dry Sandy Highveld Grassland; Dry Clay Highveld Grassland; Moist Cool Highveld Grassland; Moist Cold Highveld Grassland; North Eastern Mountain Grassland; Moist Sandy Highveld Grassland; Wet Cold Highveld Grassland (limited); Moist Clay Highveld Grassland; Patches Afromontane Forest (very limited)
Altitude (masl)	1 100 – 2 100
Mean annual precipitation (mm)	400 to 1 000
Rainfall seasonality	Early to late summer
Mean annual temperature (°C)	12 to 20
Mean annual runoff (mm)	5 to > 250

3.1.2. Climate

According to the Köppen-Geiger climate type map of Africa (Peel *et al*., 2007), Johannesburg is classified as Cwb, namely warm temperate climate (C), with dry winters (w) and warm summers (b). Johannesburg falls within the Mesic Highveld Grassland Bioregion (Gm), which has a mean annual precipitation (MAP) of 726 mm, a mean annual potential evaporation (MAPE) value of 1 958 mm, and a mean annual soil moisture stress (MASMS) value of 74% (Mucina *et al.,* 2006). This data indicates that the region experiences approximately 270 days a year where evaporative demand exceeds soil moisture supply. The average rainfall, taken over a 30-year period for the Rand Water supply area, is 654.25 mm. The area can experience severe and frequent frosts in winter (Mucina and Rutherford, 2006).

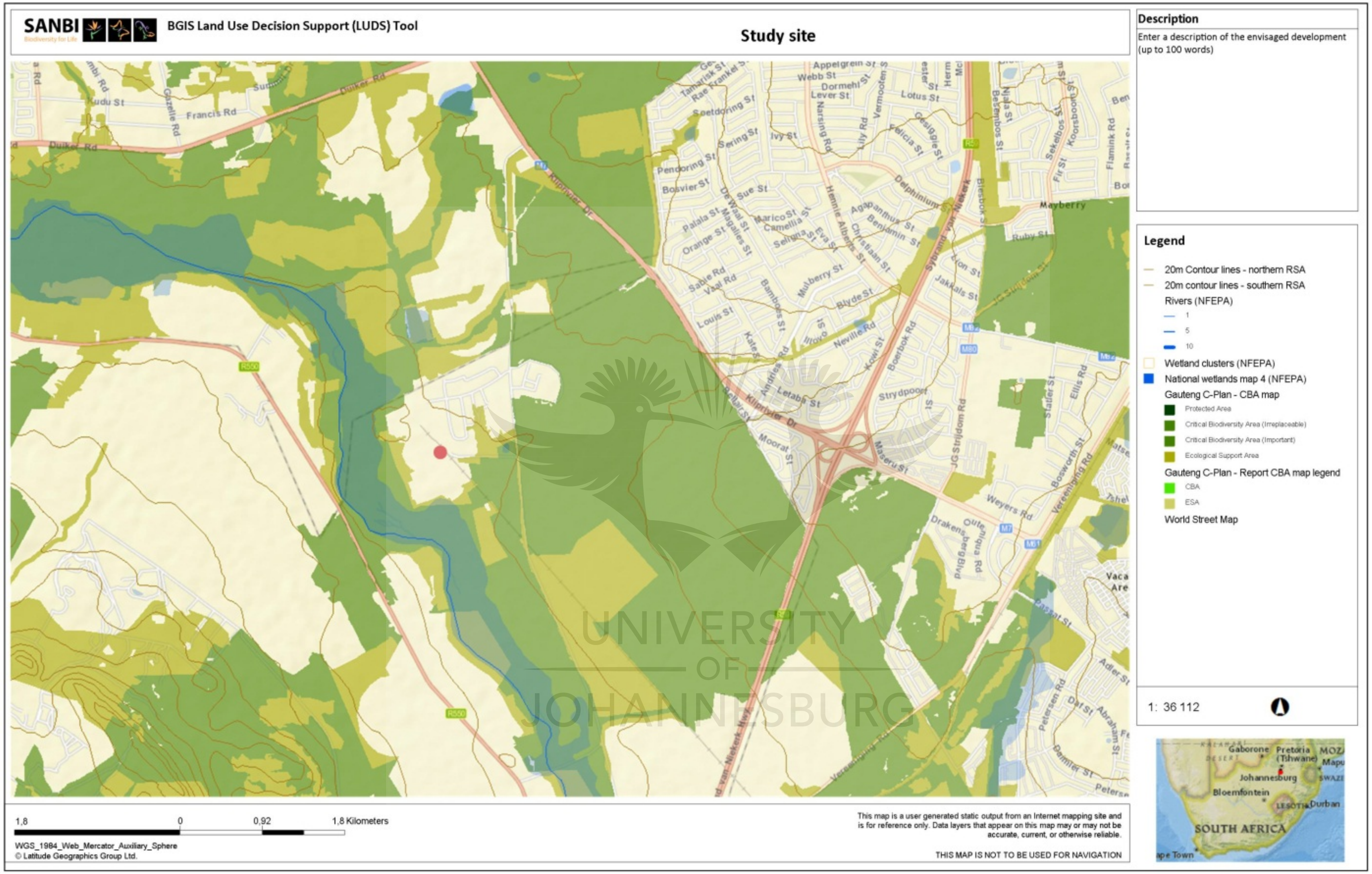

Figure 5. The study site (red dot) is located in Alberton/Johannesburg South at Environmental Management Services Department, Rand Water, Johannesburg, Gauteng (source: SANBI BGIS, accessed 15 May 2018).

3.1.3. Vegetation

The site is located within the Grassland biome, specifically in the Klipriver Highveld Grassland, which is a listed threatened terrestrial ecosystem (Figure 6) (SANBI, 2018). This area includes five threatened vegetation types and little of it is under formal protection (SANBI, 2013). It falls within the Carletonville Dolomite Grassland (Gh 15) vegetation type, of which 1.8% of the area is currently protected and is therefore described as poorly protected and vulnerable. Important vegetation taxa that can be found in this area includes graminoids such as *Heteropogon contortus* (Spear Grass), *Themeda triandra* (Red Grass), *Eragrostis curvula* (Weeping Love Grass), *Melinis repens* (Natal Red Top), and *Elionurus muticus* (Silver Grass), herbs such as *Acalypha angustata* (Forest False Nettle), *Helichrysum caespititium* (Speelwonderboom), *Senecio coronatus* (Woolly Grassland Senecio), *Hilliardiella oligocephala* (Bitterbossie), and *Dicoma anomala* (Fever Bush), and shrubs such as *Ziziphus zeyheriana* (Buffalo Thorn), *Searsia magalismontana* (Bergtaaibos), *Indigofera comosa*, and *Tylosema esculentum* (Gemsbok Bean). Species endemic to the area include the succulent shrub *Delosperma davyi* (Ice Plant) (Mucina and Rutherford, 2006).

3.1.4. Geology

The study site is underlain primarily by dolomite from the Malmani Subgroup, rocks that form part of the Transvaal Supergroup (Vermaak, 2009). This subgroup supports shallow Mispah and Glenrosa soils, with sporadically occurring deeper red to yellow apedal soils from the Hutton and Clovelly forms (Mucina and Rutherford, 2006). Soils in this area can also have a low to medium base status, and are freely drained and structure-less. Characteristics of this soil type are restricted soil depth, excessive drainage, high erodibility, and low natural fertility (SANBI, 2018).

3.1.5. Land use

The area surrounding the study site is primarily used for agriculture such as maize, rangeland, including cattle and sheep, and gold mining (SANBI, 2013).

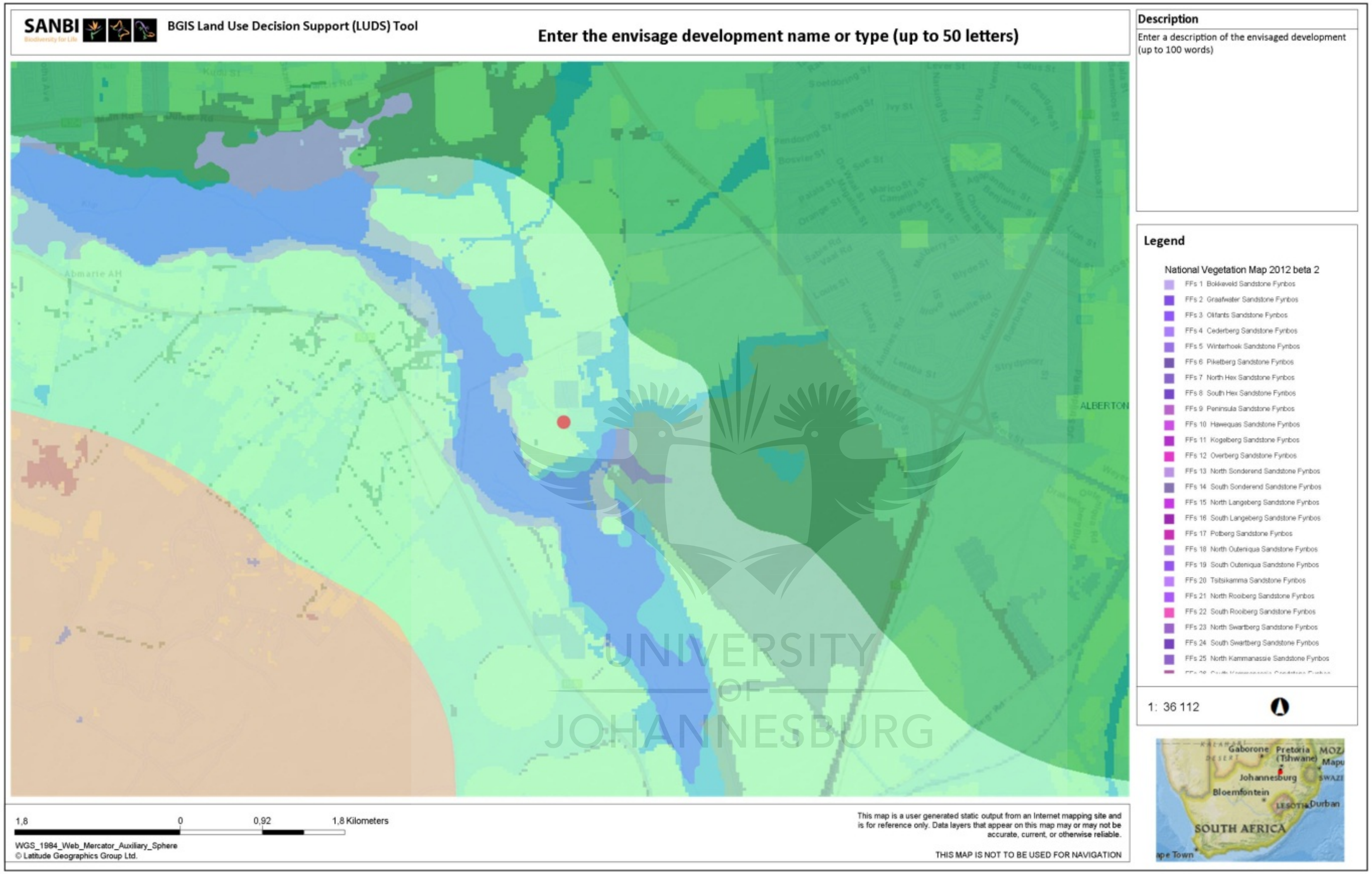

Figure 6. The study site (red dot) is located within the Carletonville Dolomite Grassland vegetation type, in Alberton/Johannesburg South at Environmental Management Services Department, Rand Water, Johannesburg, Gauteng (source: SANBI BGIS).

3.2. Site selection

Suitable sites were identified at Environmental Management Services Nursery (Figure 7). Three locations were pinpointed that were positioned close to a greywater source, and were suitable in size for the capacity of the CW. There are thirty staff members based at the main office and nursery sites and twenty staff based at the Zwartkopjes site.

There are a number of criteria that need to be taken into account when selecting a site for artificial wetland construction, as per Wolmarans (2017). The sites at Rand Water were selected according to the following:

- The treatment facility, i.e. CW, must be in close proximity to the source of greywater and must receive it directly from the source;
- The site must be in full sun;
- The site must be on a downhill slope of at least 0.5%;
- There needs to be adequate space to perform any necessary maintenance;
- Care must be taken on areas with underlying dolomite and the risk of sinkhole formation;
- Construction of CW should not be done in existing natural wetlands; and
- Treated greywater should be used for irrigation of gardens and landscapes, and not of food gardens.

The first site, referred to as the main office artificial wetland (MO-AW) is positioned outside the main office block, in close proximity to the outlet pipes from the ablution facilities' hand basins as well as the kitchen facility's sink (Figure 8). The treated greywater is discharged through the outlet pipes into a landscaped garden similar to those that can be found on residential properties with stand-alone or cluster homes.

Figure 7. Google Earth map showing the location of sites identified for CW at Environmental Management Services Department, Rand Water, Johannesburg, Gauteng (Google Earth, 2017).

Figure 8. Site identified as MO-AW at Environmental Management Services Department, Rand Water, Gauteng. The red polygon indicates the intended location of the wetland construction. This site is located adjacent to a kitchen and male and female bathrooms (no showers) (Images: S. Stelli, 2018).

The second site, referred to as the nursery artificial wetland (N-AW) is positioned outside the secondary office on site, and receives greywater from the sink of the adjacent kitchen facility, and from the basins and showers of the adjacent ablution facilities (Figure 9). The treated greywater is discharged through an outlet pipe into a landscaped garden, similar to those that can be found on residential properties with stand-alone or cluster homes.

Figure 9. Site identified as N-AW at Environmental Management Services Department, Rand Water, Gauteng. The red polygon indicates the intended location of the wetland construction. This site is located adjacent to a kitchen and male and female bathrooms (with showers) (Images: S. Stelli, 2018).

The third site is located alongside ablution facilities and receives water from basins and showers only. The site is called Zwartkopjes artificial wetland (Z-AW) (Figure 10). Treated greywater is collected in a submerged 700 litre Jojo Vertical Water Tank, also referred to as the effluent tank. The water tank has a level sensor that activates when a certain water level is reached and turns a pump on. The pump pumps water out of the tank through a hosepipe and into the adjacent landscaped gardens.

Figure 10. Site identified as Z-AW at Environmental Management Services Department, Rand Water, Gauteng. The red polygon indicates the intended location of the wetland construction. This site is located adjacent to male and female bathrooms (with showers) (Images: S. Stelli, 2018).

3.3. Constructed wetland (CW) design

Due to the space available for the CW, the size of the systems was designed to be suitable to accommodate the greywater produced by four people. Functionally, the CW were designed with the purpose of being implemented in households with an average of four people living in one house. The guideline used for this was developed by the Joint Standards Australia/Standards New Zealand (A/NZ) Committee (2012). The document recommends using a 6 m^2 wetland area to treat the daily wastewater (excluding blackwater) of 30 L/p/d applied per square metre as produced by four people in a household. This is equivalent to 180 L of wastewater per day. A suitable depth for the wetland is 40 cm, with a water depth of 5 cm below the surface of the system, and a gravel porosity of 40%, which would equate to a retention time of 4.7 days (A/NZ Standard, 2012).

The design and construction of the CW systems was implemented by an independent environmental consulting company, GIBB Engineering and Architecture (Pty) Ltd. GIBB was presented with a list of requirements for the systems:

- Accommodate a typical household of 4 people;
- Treat water to a suitable standard for garden use;
- Simple construction (can be constructed with locally available materials);
- Simple operation and maintenance;
- Compact design to accommodate typical small residential gardens;
- Aesthetically pleasing design, forms part of a residential garden;
- Habitat creation and biodiversity;
- No standing/stagnant water;
- System to adhere to all relevant legislation/by-laws that apply to the use of greywater; and
- Vegetation species to be suitable for Gauteng climate and to tolerate drought, frost and saturated conditions.

Wolmarans (2017) recommended the following equation to determine the size of the wetland:

Size required = *X* (amount of people in house) x 1.5m

The Australian/New Zealand (A/NZ) standards for on-site domestic wastewater management (2012) use the number of bedrooms in a home to extrapolate the number of people living in the home and the volume of wastewater that is produced daily. This was used to determine the artificial wetland area, length, and width.

3.4. Wetland construction

There were six main structural components that were taken into consideration when designing the CW (Wolmarans, 2017), namely the excavated basin, the impermeable lining to prevent wastewater leakage or groundwater infiltration, gravel media, wetland plants, inlet and outlet structures to ensure uniform flow distribution, an adjustable water level control device at the outlet, and sampling points at the inlet and outlet points, consisting of collection jugs. The construction of the wetlands was done as per Wolmarans (2017).

The basins were excavated at each identified point (see *3.1. Site Selection*). Suitable sites were measured and then demarcated with safety tape. Plumbing supplies such as 50 mm

PVC pipes, 50 mm PVC straight sockets, 50 mm end caps, 50 mm PVC elbows, 50 mm PVC 45° elbows, and 50 mm tees were used to connect the outlet pipes from the bathrooms and kitchens to the inlet pipes into the CW. This allowed untreated greywater to flow directly from the source into the CW, thereby preventing the pooling of water, and potential unpleasant odours. It was ensured that the top level of the basin was lower than the height of the inlet and source of greywater, to allow gravity flow of water into the system to occur and to reduce the need for a pump. The floor of the basin was made level and flat. A durable, flexible, and impermeable plastic liner was placed along the bottom of the basin. A single sheet (3 m in width) of linear low density polyethylene (LLDPE) of 0.75-1 mm thickness was used. This is to prevent the infiltration of untreated greywater into the groundwater.

Once the basins were excavated and lined, they were filled with crushed angular stone / gravel of between 13 and 19 mm in size to the level of the basin. The gravel was washed with tap water before use to remove any sediment or organic matter that would affect the efficiency of the system. The gravel was then levelled using a rake. Once the gravel was levelled, the basin was filled with tap water to the level of the gravel.

Each CW was also fitted with a primary treatment system, namely a filtration device, to allow for solids and organic matter such as lint, hair, food, and other sediment to be removed, as well as to reduce the amount of grease and oil that moves through the system. The aim of this project was to identify easily available materials that can be sourced from local hardware stores, and that can be fitted by the homeowner. Consequently, the filter device and grease trap was made using a swimming pool rainwater pit, a plastic grid, a 20 cm plant pot, and a swimming pool weir basket. A hole to fit a 25 mm plastic pipe was cut into the side of the rainwater pit and pot plant. The rainwater pit and pot plant were fitted with a 25 mm PVC elbow to direct water into the basin, and placed into the ground within the gravel of the CW. A weir basket was placed into the pot plant and the entire device was then fitted with the grid. The inlet pipe was then laid over the grid to allow greywater to flow into and through the filter device and directly into the gravel of the CW. An outlet pipe to direct treated greywater into the landscaped gardens was fitted at the further end of the basin, into the plastic liner at a point just below the final water level, using 50 mm PVC pipe and the 50 mm PVC socket.

Selected wetland plants were planted in each basin. Plants were selected that are indigenous to the Highveld and therefore tolerant of frosty winters. Young plants were planted from 1 - 1.5 litre containers at 4 - 6 plants per square meter. Soil from the roots was removed to prevent clogging of the pores between the gravel, and plants were planted directly into the gravel with no other media. Plants were not placed adjacent to the inlet and outlet pipes to allow for clear movement of water. Plants used included *Cyperus prolifer* (Miniature Papyrus), *Cyperus denudatus*, *Schoenoplectus brachyceras* (Water Reed), *Juncus oxycarpa*, *Eleocharis dregeana* (Finger Sedge), *Fimbristylis complanata*, *Berula erecta* (Water Parsnip), *Crinum bulbispermum* (Orange River Lily), *Kniphofia ensifolia* (Torch Lily), and *Zantedeschia aethiopica* (Arum Lily). Most plant species selected for the CW are readily available at local and indigenous garden centres and nurseries.

Once the plants were planted, the water level in the basins was lowered to 5 cm below the surface of the gravel. This is the recommended depth according to the A/NZ standard (2012) to prevent ponding of water and odours.

The CW excavated alongside the main office (MO-AW) (Figure 11) is 4 400 mm in length, 1 900 mm in width, and 450 mm in depth. The N-AW (Figure 12) is 3 000 mm in length, 2 000 mm in width, and 450 mm in depth. The Z-AW is 4 400 mm in length, 2 000 mm in length, and 450 mm in depth (Figure 13). The Z-AW was fitted with a storage tank, whereby treated greywater can be stored and then pumped out for use when necessary. A 750 litre plastic Jojo water tank was dug into the ground adjacent to the further end of the basin. The outlet pipe from the basin was connected to an inlet pipe into the tank, just below the water level of the basin. A submersible pump was fitted into the tank, with a level switch that is activated when the water in the tank reaches a certain level. The pump then pushes water through a hose pipe into the surrounding landscaped gardens (Figure 14).

Figure 11. a) Image of the MO-AW. The location of the CW is designated with a red polygon (Image: S Stelli, 2017).

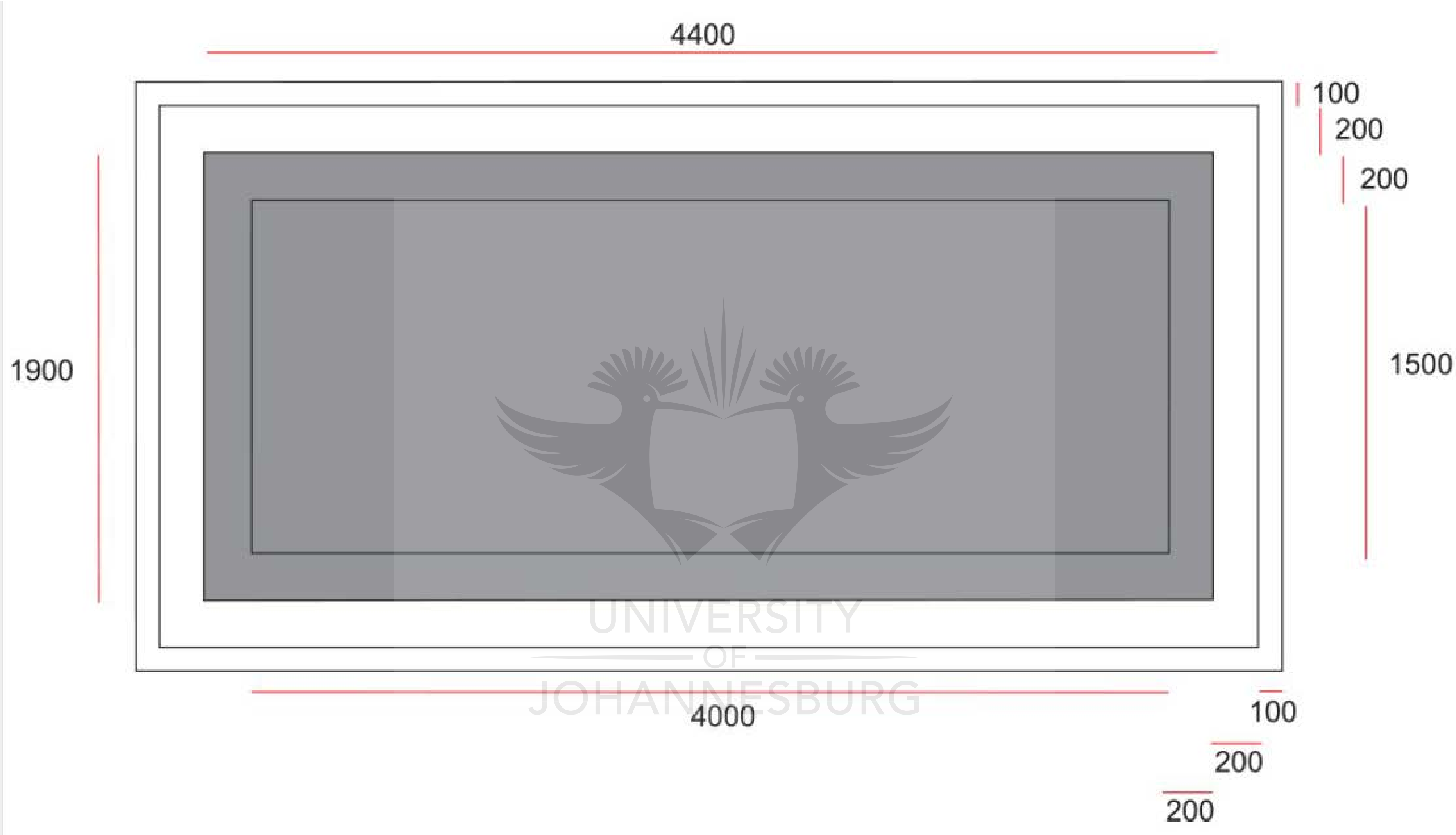

Figure 11. b) Design parameters of the MO-AW (Image: Wolmarans, 2017).

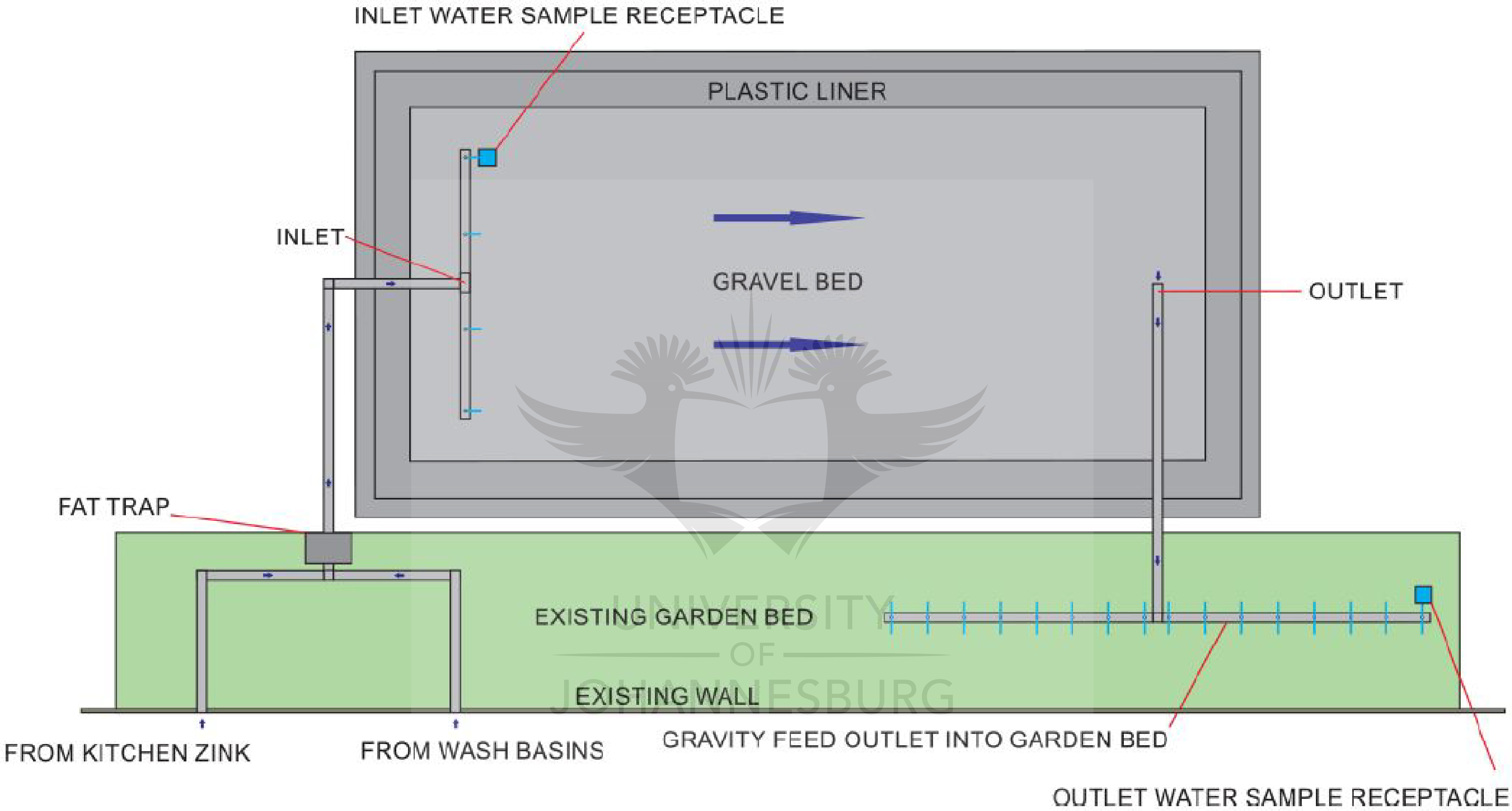

Figure 11. c) Water circulation of the MO-AW (Image: Wolmarans, 2017).

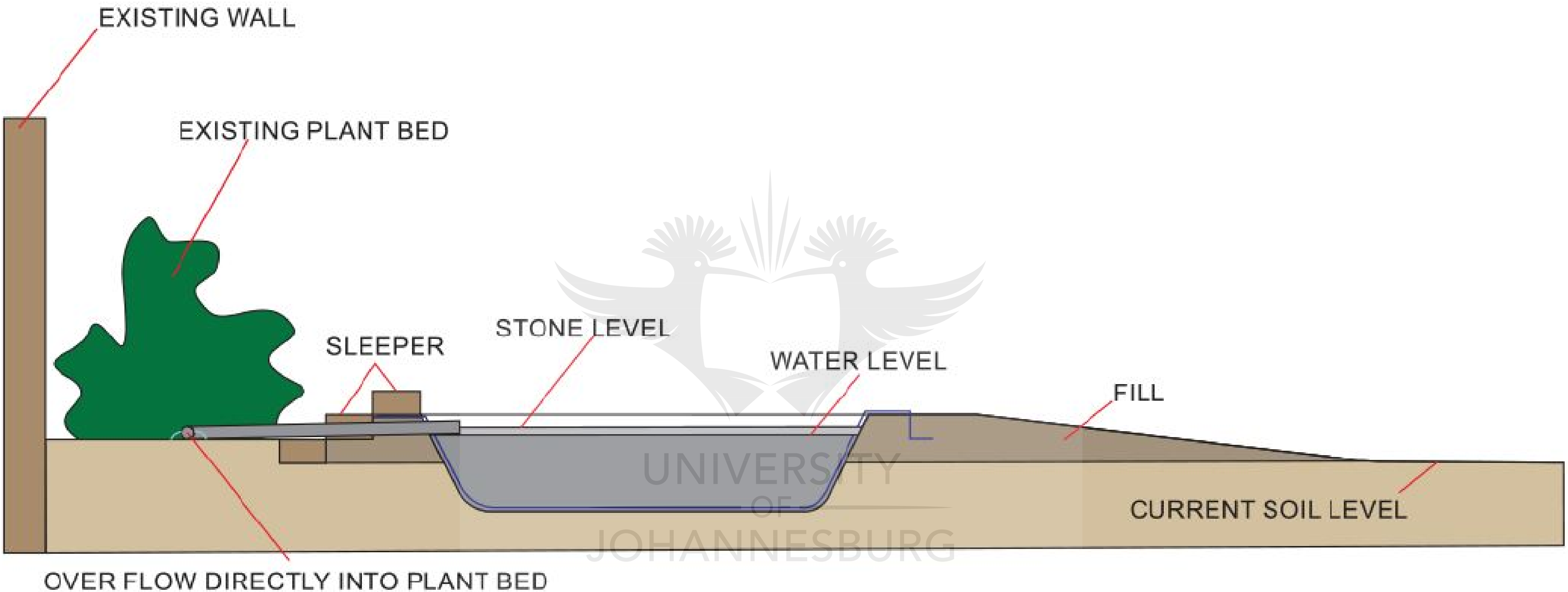

Figure 11. d) Gravity feed for the MO-AW located at Zwartkopjes, Rand Water (Image: Wolmarans, 2017).

Figure 12. a) Image of the N-AW. The location of the CW is designated with a red polygon (Image: S Stelli, 2017).

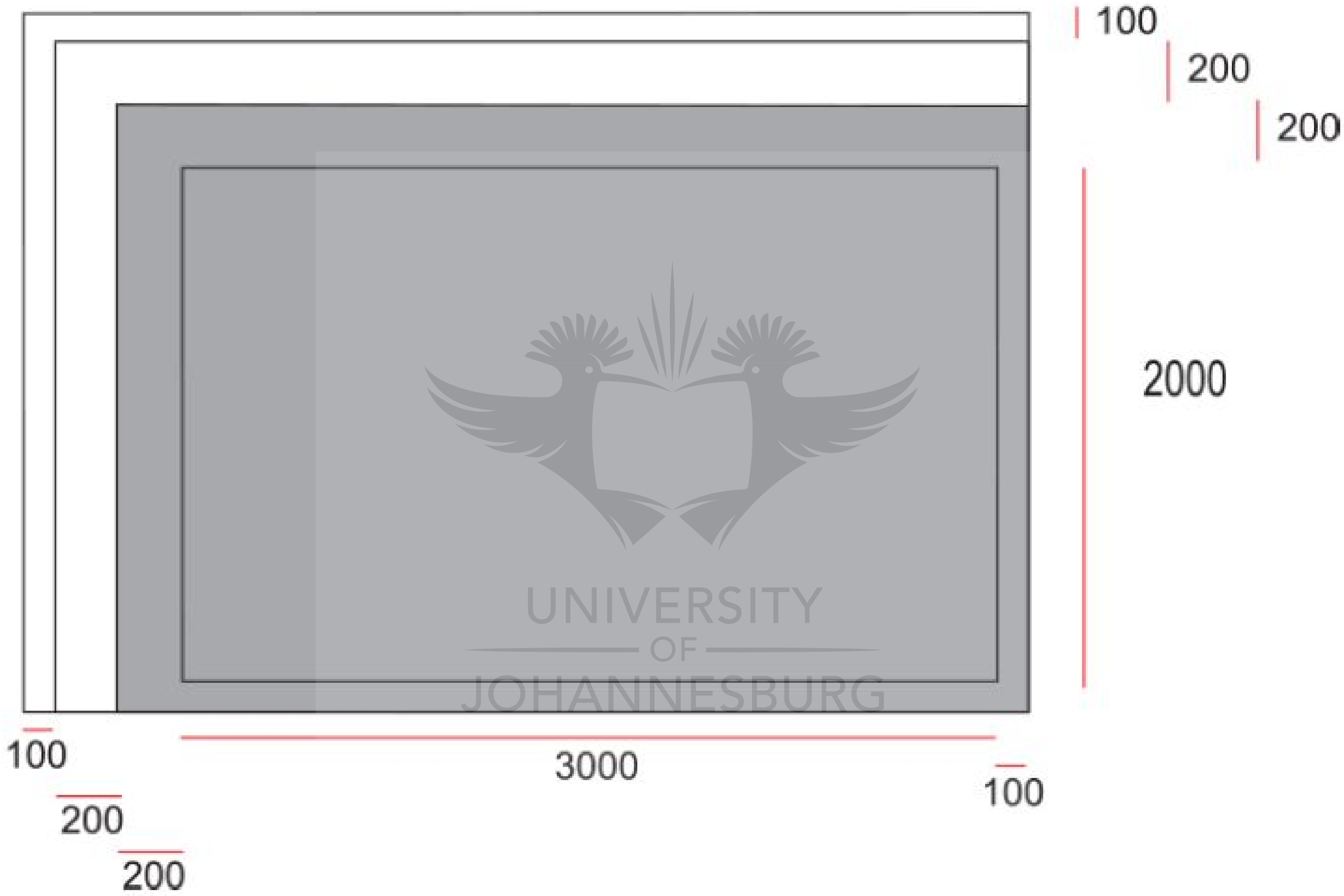

Figure 12. b) Design parameters of the N-AW located at Zwartkopjes, Rand Water (Image: Wolmarans, 2017).

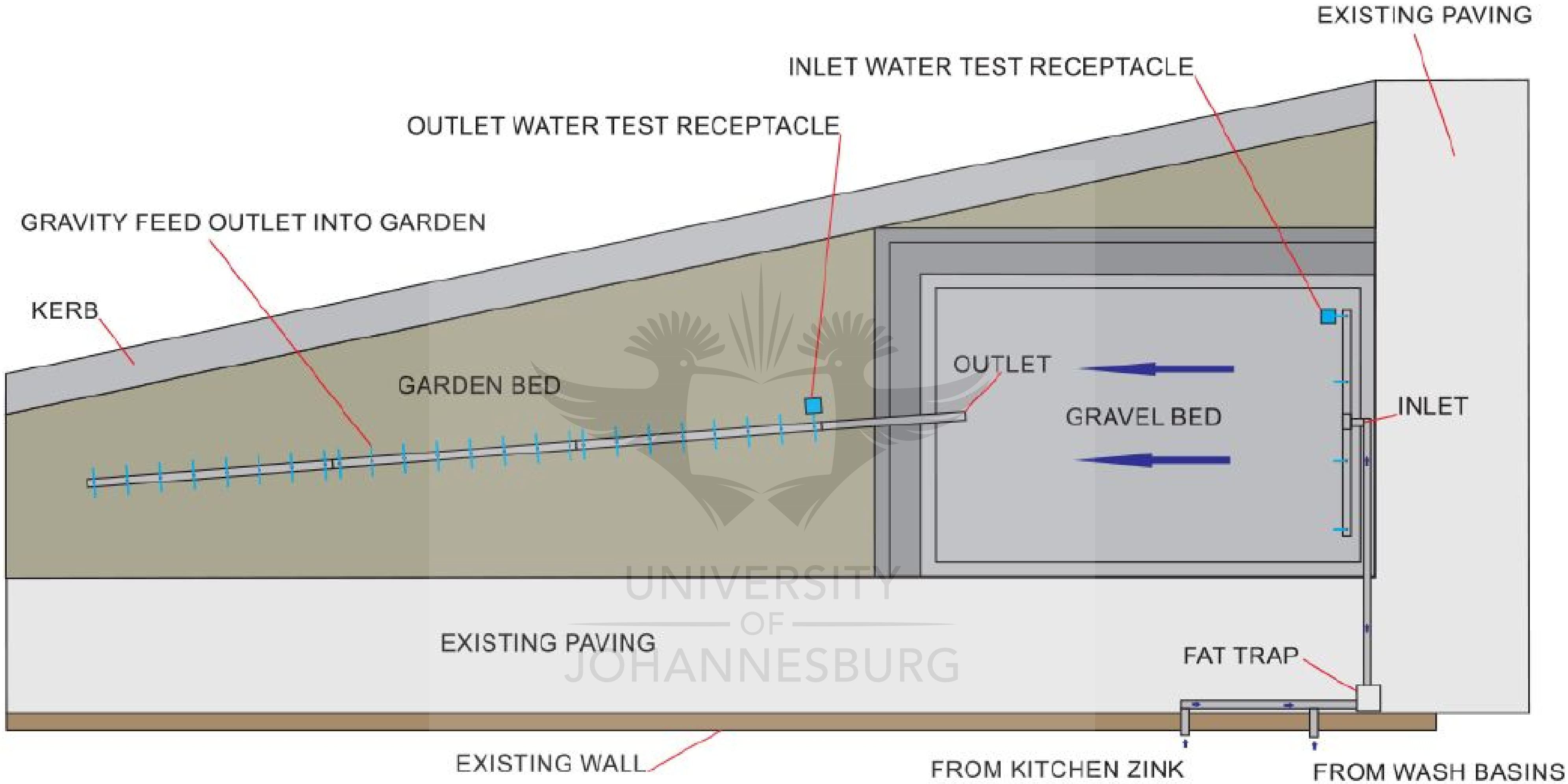

Figure 12. c) Water circulation and gravity feed for the N-AW located at Zwartkopjes, Rand Water (Image: Wolmarans, 2017).

Figure 13. a) Image of the Z-AW. The location of the CW is designated with a red polygon (Image: S. Stelli, 2018).

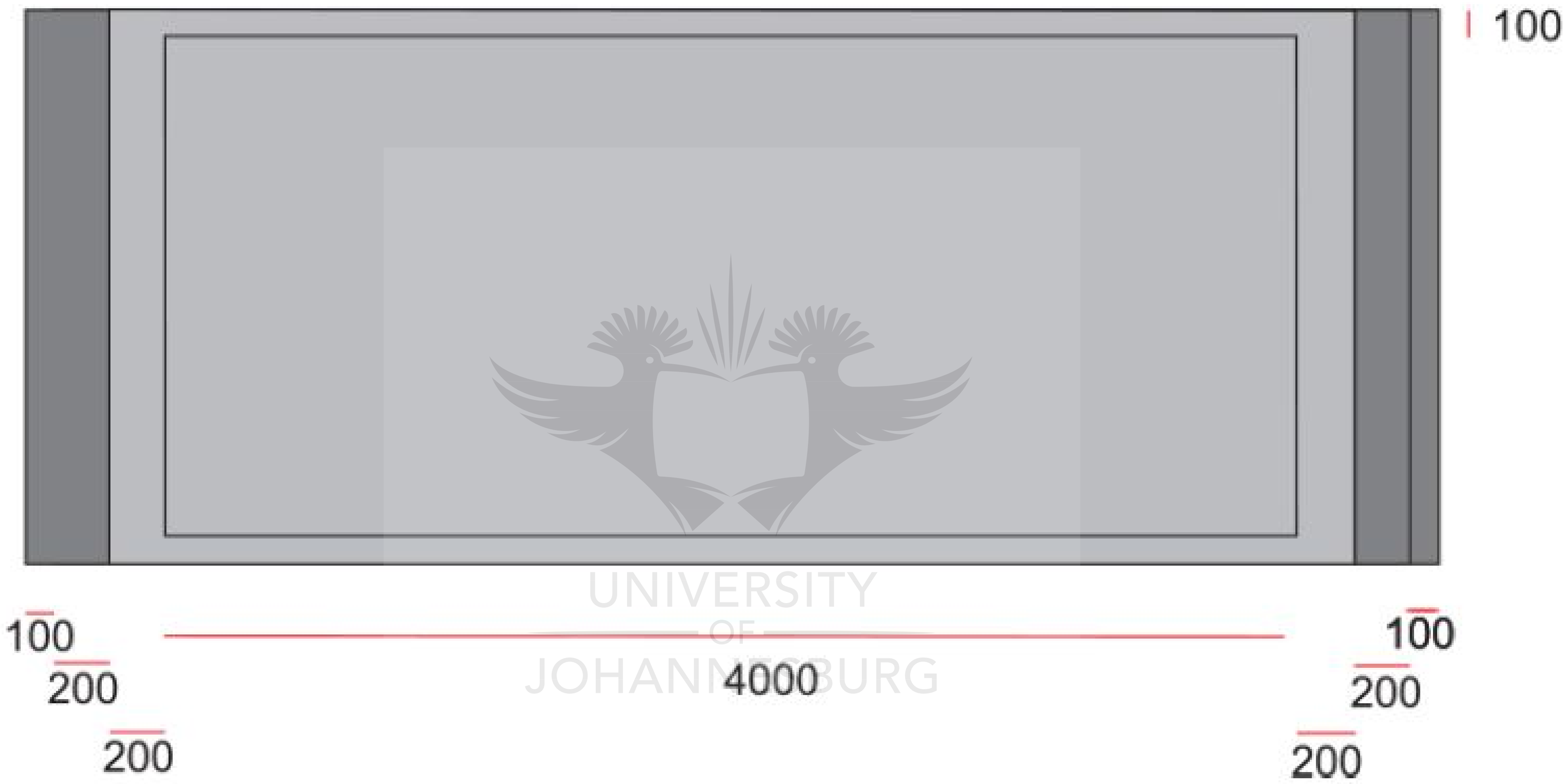

Figure 13. b) Design parameters of the Z-AW located at Zwartkopjes, Rand Water (Image: Wolmarans, 2017).

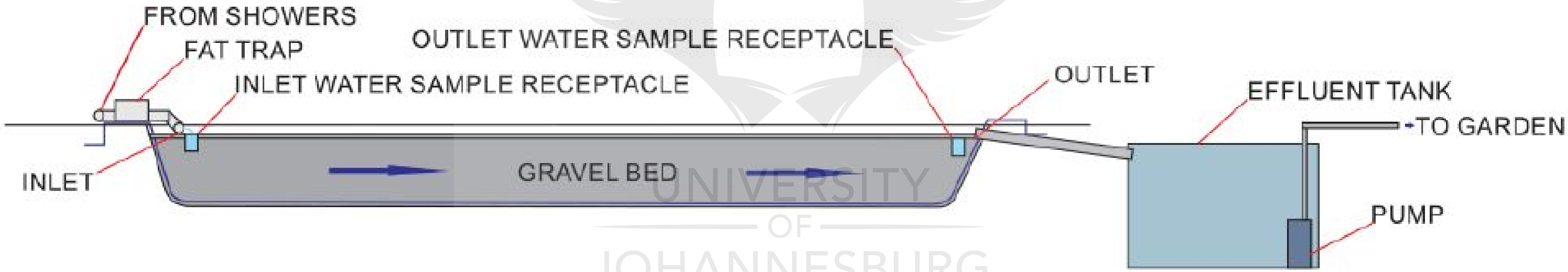

Figure 13. c) Water circulation and gravity feed for the Z-AW located at Zwartkopjes, Rand Water (Image: Wolmarans, 2017).

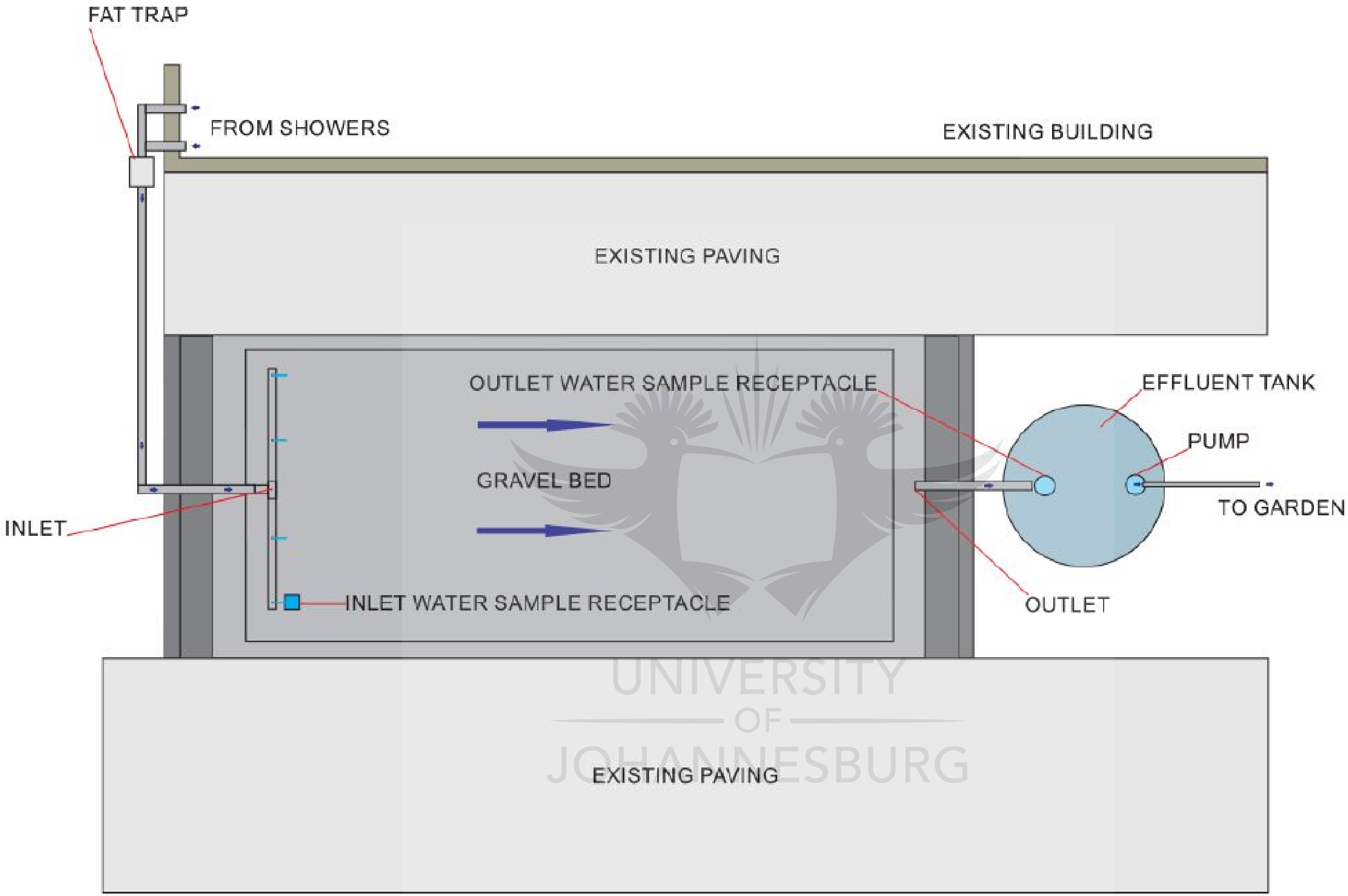

Figure 13. d) Gravity feed for the Z-AW located at Zwartkopjes, Rand Water (Image: Wolmarans, 2017).

Figure 14. Sump or storage tank installed adjacent to the Z-AW located at Zwartkopjes, Rand Water, to collect and store treated greywater for use in the surrounding landscaped gardens when required (images: Wolmarans, 2017).

3.5. Water quality sampling and analysis

Twenty-one water quality parameters were measured and analysed. These parameters were chosen based on the range of parameters that have been monitored in similar studies conducted on the treatment of greywater (e.g. Roesner *et al*., 2006; Avery *et al*., 2007; Jokerts *et al*., 2009; Rodda *et al*., 2011; Arden and Ma, 2018). The systems were monitored over a period of 9 months from August 2017 until May 2018. During this time, water quality was assessed twice a month for the first five months, and then once a month from March 2018 to May 2018. In total there were 11 sampling events. Two sample collection points were analysed per system, at the inlet of untreated greywater into the CW, and at the outlet of treated water from the CW. Water quality samples were collected and analysed according to the Rand Water Analytical Services Sampling Procedure for Biology and Chemistry 3.3.1.10.1 (2017).

Samples were taken between 09:00 and 10:00 am on the day of sampling. Latex gloves and safety boots were worn by the sampler to prevent contact with potentially contaminated water. Photos were taken of the CW systems for each sampling event, using the sampler's

Samsung J7 cellphone camera, to photographically document plant growth and health. At the inlet of untreated greywater from the source into the system (from the water collected within the filter device), water was collected using sampling bottles specific to the water quality parameter being measured. At the outlet point into the landscaped gardens, treated greywater was collected from a clean sampling bottle placed at the outlet. All bottles were labelled with specifically printed laboratory sample bottle labels. Bottles were transported to the laboratory immediately after sampling, upright in a cooler box with ice packs. Analyses were conducted by the Scientific Services: Analytical Services Laboratory, which is a SANAS (South African National Accreditation System) accredited laboratory that complies with ISO/IEC 17025. An accredited certificate of analysis was emailed to the sampler approximately one week after sampling, according to SANAS requirements. It must be noted that information regarding the specific type and model of instruments used by Rand Water to analyse and measure samples, is generally viewed as confidential and not to be shared with the general public, as per the Rand Water Analytical Services Sampling Procedure for Biology and Chemistry 3.3.1.10.1 (2017).

3.5.1. Microbiology

For the microbiology parameter, namely *E. coli*, samples were taken with a 50 mL sterile plastic disposable micro bottle (M-500ML_P) that had been radiated and preserved pre-sample with sodium thiosulfate. The sample bottle was left closed until the sample was taken to prevent contamination. The bottle was filled to 2 cm below the top and the lid was replaced tightly. Care was taken not to touch the inside of the bottle in order to prevent contamination. Once the sample was taken, it was placed upright in a cooler box with frozen ice bricks. The same sampling method was used to sample at the inlet point to the system, where untreated greywater entered the CW, and at the outlet collection point, where treated water exited the system, for all three CW.

Samples were analysed at Rand Water's Analytical Services Chemistry Laboratory in Vereeniging. The analysis for the detection and enumeration of *E. coli* was done using the Colilert-18 / Quanti-Tray and Colilert-18 / Quanti-Tray 200 method in MPN (most probable number)/100mL (Rand Water, 2017).

3.5.2. Inorganics

Inorganics, namely Ca (mg/L), Mg (mg/L), Cl (mg/L), SO_4 (mg/L), NO_3 (mg/L), B (µg/L), K (mg/L), Na (mg/L), pH, EC, TDS (mg/L), alkalinity (mg/L calcium carbonate ($CaCO_3$)), and turbidity (NTU) were sampled using 1 L plastic bottles (_P). The sample bottles were filled to the rim to prevent air bubbles and the lid was screwed on tightly. Samples were taken from the inlet point of untreated greywater into the system, and at the outlet point of treated water from the system, for all three CW.

Samples were analysed at Rand Water's Analytical Services Chemistry Laboratory in Vereeniging. The analyses for EC, pH, and alkalinity were done using the Multiparameter Analysis with One Click®. Turbidity was analysed using a photometer. Nitrates (NO_3), SO_4, and Cl were analysed using the IC_LOW (Ion-chromatography) technique. Total dissolved solids (TDS) was measured using a gravimetric analyser (105 ºC). Metals such as Ca, Mg, B, K, and Na were measured using the ICP (Inductively Coupled Plasma) technique with a spectrometer (Rand Water, 2017).

3.5.3. Organics

Organics such as total organic carbon (TOC) (mg/L as C) and oil and grease (mg/L) were sampled using 1 L Schott glass sample bottles with blue caps (_G). It was ensured that bottles were filled to the rim to prevent air bubbles and the lid was screwed on tightly. Samples were taken from the inlet point of untreated greywater into the system, and at the outlet point of treated water from the system, for all three CW.

Samples were analysed at Rand Water's Analytical Services Chemistry Laboratory in Vereeniging. Total organic carbon (TOC) was measured using a TOC-analyser, and oil and grease was measured as n-Hexane-extractable material (HEM) using an analytical balance (Rand Water, 2017).

3.5.4. Dissolved oxygen (DO)

Dissolved oxygen (DO) was sampled using 250 mL glass bottles with glass/plastic stoppers (G_DO). The bottle was filled halfway with the sample whereby 1 mL of manganese SO_4 and 1 mL of alkaline iodide-azide solution was added. The bottle was then filled to overflowing with the sample to prevent the formation of air bubbles. The lid was replaced carefully and the bottle was inverted several times to allow mixing to occur. Samples were taken from the inlet point of untreated greywater into the system, and at the outlet point of treated water from the system, for all three CW.

Samples were analysed at Rand Water's Analytical Services Chemistry Laboratory in Vereeniging, using a standard DO sensor (Rand Water, 2017).

3.6. Statistical analyses

Statistical analyses were done using paired samples *t*-tests to compare the difference between the concentrations of water quality parameters before treatment and after treatment, for each of the three CW. One-way ANOVAs and post-hoc Tukey Studentized Range tests (α, $P = 0.05$) were used to compare differences in water quality parameters of greywater before treatment between the three CW, and after treatment between the three CW. The correlation coefficient was calculated to analyse the relationship between average temperature per day for each sampling date, and plant health for each wetland. All statistical analyses were completed using IBM® SPSS® 21.0 Predictive Analytics software and Microsoft Excel 10.

3.7. Changes in plant growth and 'health'

Patterns in the growth and 'health' of the wetland plants were observed and analysed using photographic images, and a plant health rating scale (Table 10) developed by the Water Wise team at Rand Water (Stelli and Mphomane, 2016). The rating scale is based on the observational percentages of six criteria, including leaf discolouration, and the presence of pests and fungal infestations on plants. Plants were visually analysed for the criteria listed in the rating scale and then given a score based on the percentage range listed for each criteria. The percentage range into which the score falls was then assigned with a numerical value. For example, a plant with 30% of its leaves brown and dry was assigned with a score of 2 for that specific criterion. The numbers were then added up to give a value that was converted into overall 'percentage plant health' for the CW. Constructed wetlands (CW) with a higher overall percentage were rated as 'healthier' than those with a lower percentage. The rating of plant health and growth was done for all the plants collectively, for each CW.

3.8. Climatic conditions

Cumulative rainfall (mm) and average temperature (°C) per day was recorded for each sampling date over the sampling period, August 2017 to May 2018. This was done with the Zwartkopjes site's weather station, Campbell Scientific CR10x, which records cumulative rainfall, humidity, wind speed, wind direction, and temperature.

3.9. Do-it-yourself (DIY) manual

Once the design and effectiveness of the system was verified, a manual was drawn up that will be made accessible to the general public (Appendix A). The manual was designed to guide homeowners through the process of purchasing the equipment required for the system, as well as how to construct it themselves and use it for the treatment of household greywater.

Table 10. Plant health rating scale used to determine plant health and growth patterns for wetland plants planted in three CW at Zwartkopjes, Rand Water (as per Stelli and Mphomane, 2016).

		Health rating (proportional basis)*			
Criteria	**Poor**	**Weak**	**Good**	**Excellent**	**Criteria**
Leaf health **All leaves are brown, dry, and crunchy when touched (still on tree or on ground surface).**	0-10%	10-40%	40-80%	80-100%	**Leaf health** All leaves are green, strong, and healthy.
Leaf discolouration **Leaves have a yellow colour, or are mottled in appearance.**	0-10%	10-40%	40-80%	80-100%	**Leaf discolouration** Leaves are bright green, and not mottled or discoloured.
Plant pests **Leaves and stems show signs of plant pests e.g. aphids, scale, spider mites, mealy bugs etc.**	0-10%	10-40%	40-80%	80-100%	**Plant pests** No evidence of pests on leaves, branches or stems of plants.
Fungus/diseases **Leaves and stems show signs of diseases and/or fungus e.g. leaf spot, blight, mould, mildew, rot etc.** **.**	0-10%	10-40%	40-80%	80-100%	**Fungus/diseases** No evidence of diseases or fungus on leaves, branches or stems.
Flowers **Flowers have died or fallen off the plant.**	0-10%	10-40%	40-80%	80-100%	**Flowers** Flowers are healthy, fresh, turgid and remain on the plant**.**
Abundance (% of surface area) and height **Plants are below 20 cm in length and show sparse growth across surface area of wetland.**	0-10%	10-40%	40-80%	80-100%	**Abundance (% of surface area) and height** Plants are above 150 m in length and show expansion in growth across the surface area of the wetland.

**0-10% = 1; 11-40% = 2; 41-80% = 3; 81-100% = 4.*

Chapter 4: Results

4.1. Paired samples *t*-test comparisons for water quality parameters

Three CW were assembled at Rand Water's Zwartkopjes site from 22 to 29 June 2017. Greywater was directed into the CW immediately after construction was completed. As the wetlands were installed mid-winter, it was expected that the efficiency of water treatment would be impaired due to the cold temperatures and frost experienced on the Highveld, and the resultant stagnation in the growth rate of the wetland plants. In addition, it was noted that the design is expected to have a 'settling' period of between 1 to 3 months to allow for the growth of biofilms on the gravel surfaces, and establishment of the wetland plants. The first samples were taken on the 23rd August 2017. Twenty-one physico-chemical and microbiological water quality parameters were analysed for each CW. Full SANAS-accredited water quality reports can be found in Appendix B. For ease of reporting, the parameters have been divided up into groups as follows:

Physical parameters:

- EC;
- pH;
- Alkalinity;
- DO;
- Turbidity;
- TDS; and
- Temperature.

Anions:

- Total PO_4 (TP);
- NO_3;
- SO_4; and
- Cl.

Organics:

- TOC; and
- Oil and grease.

Metals:

- Ca hardness;
- Mg hardness;
- Mg;
- Na;
- K;
- B; and
- Ca.

Microbiological parameters:

- *E. coli.*

This follows the standards utilized in the laboratory for grouping samples, as per the Rand Water Analytical Services Sampling Procedure for Biology and Chemistry 3.3.1.10.1 (2017).

4.2. Observational changes in plant growth

The wetland plants used in the CW were observed over the sampling period, August 2017 to May 2018 for seasonal and growth patterns using a plant health rating scale developed by Stelli and Mphomane (2016). The rating scale was also used to determine the overall health of the plants and wetlands. Average temperature and cumulative rainfall for each sample day was recorded (Table 11) for analysis of the possible relationship between plant growth and health, and climate.

The correlation coefficient analysis was used to test for any correlations between plant health and growth for each CW and climatic conditions at Zwartkopjes. A correlation coefficient of +1 indicates a positive correlation between two variables i.e. as one variable increases, so does the second. A coefficient of -1 indicates a negative correlation, in other words, a decrease in one variable occurs with an increase in the other. Overall, plant health and growth appeared, observationally, to vary over the sampling period, possibly as a result of the settling or establishment necessary for the wetland plants. The presence and health off flowers seemed to vary over the seasons for each wetland, showing lower values in winter and higher values in spring and summer. The abundance and height of plants in each wetland appeared to increase over time.

Table 11. Average temperature (°C) and cumulative rainfall (mm) per day for the sampling period August 2017 to May 2018 at Zwartkopjes, Rand Water.

Sample dates	Average temperature (°C)/day	Cumulative rainfall (mm)/day
23 August 2017	11.24	0
6 September 2017	15.41	0
20 September 2017	19.61	0
11 October 2017	12.91	0
25 October 2017	23.47	0
14 November 2017	19.52	9.2
22 November 2017	20.12	0
6 December 2017	15.72	35.0
28 March 2018	16.41	0
25 April 2018	13.54	0
30 May 2018	9.73	0

The average daily temperature on site at Zwartkopjes varied over the study period with a maximum of 23.47°C in October 2017 and a minimum of 9.73°C in May 2018 (Table 11). There were only two rainfall events on sampling days during the study period, one in November 2017 and one in December 2017.

4.3. Main office artificial wetland (MO-AW)

Overall, the treatment of greywater, including kitchen sink and bathroom basin wastewater by the MO-AW resulted in a significant decrease in the amount of oil and grease and TOC, as well as in *E. coli* counts and certain anions. While there was a non-significant decrease in the amount of certain metals in greywater post-treatment, certain metals actually showed an increase in amount post-treatment (non-significant) (Table 14).

4.3.1. Physical water quality parameters analysis

Paired samples *t*-tests were used to compare the differences in twenty-one water quality parameters between pre- and post-treatment for the MO-AW (Appendix C). There was a significant difference between pre- and post-treatment for two physical water quality parameters, namely an increase in TDS (t = -3.23, P = 0.009, d.f. = 10) (Figure 15) and a decrease in turbidity (t = 5.99, P < 0.05, d.f. = 10) (Figure 16) (Table 12). There were no significant differences for any of the other physical water quality parameters of the greywater between pre- and post-treatment by the MO-AW.

Table 12. Physical water quality parameters before and after treatment by the MO-AW, including paired samples t-test results (two-tailed P- and t-values; mean ± SE) (n = 11; d.f. = 10) and applicable TWQR for the WQG/I (DWAF, 1996a). ***Bolded*** *P-values are regarded as significant at the P = 0.05 level.*

Parameter	**Before treatment**	**After treatment**	**TWQR for WQG/I**	**Paired *t*-tests**		
				P	*t*	Mean difference ± SE
EC (mS/m)	39.82 ± 4.18	54.27 ± 5.91	40	0.06	-2.17	-14.45 ± 6.68
Alkalinity (mg/L $CaCO_3$)	64.64 ± 7.35	94.18 ± 23.86	-	0.28	-1.13	-29.55 ± 26.09
pH	5.29 ± 0.14	6.33 ± 0.64	6.5-8.4	0.14	-1.61	-1.01 ± 0.64
DO (mg/L)	1.77 ± 0.88	1.28 ± 0.82	-	0.13	1.65	0.49 ± 0.3
Temperature (°C)	22.97 ± 0.81	21.03 ± 2.29	-	0.32	1.05	1.94 ± 1.86
TDS (mg/L)	239.91 ± 31.88	338.64 ± 36.48	-	**0.01**	-3.23	-98.73 ± 30.54
Turbidity (NTU)	765.0 ± 114.5	97.82 ± 17.48	-	**<0.05**	5.99	667.18 ± 111.38

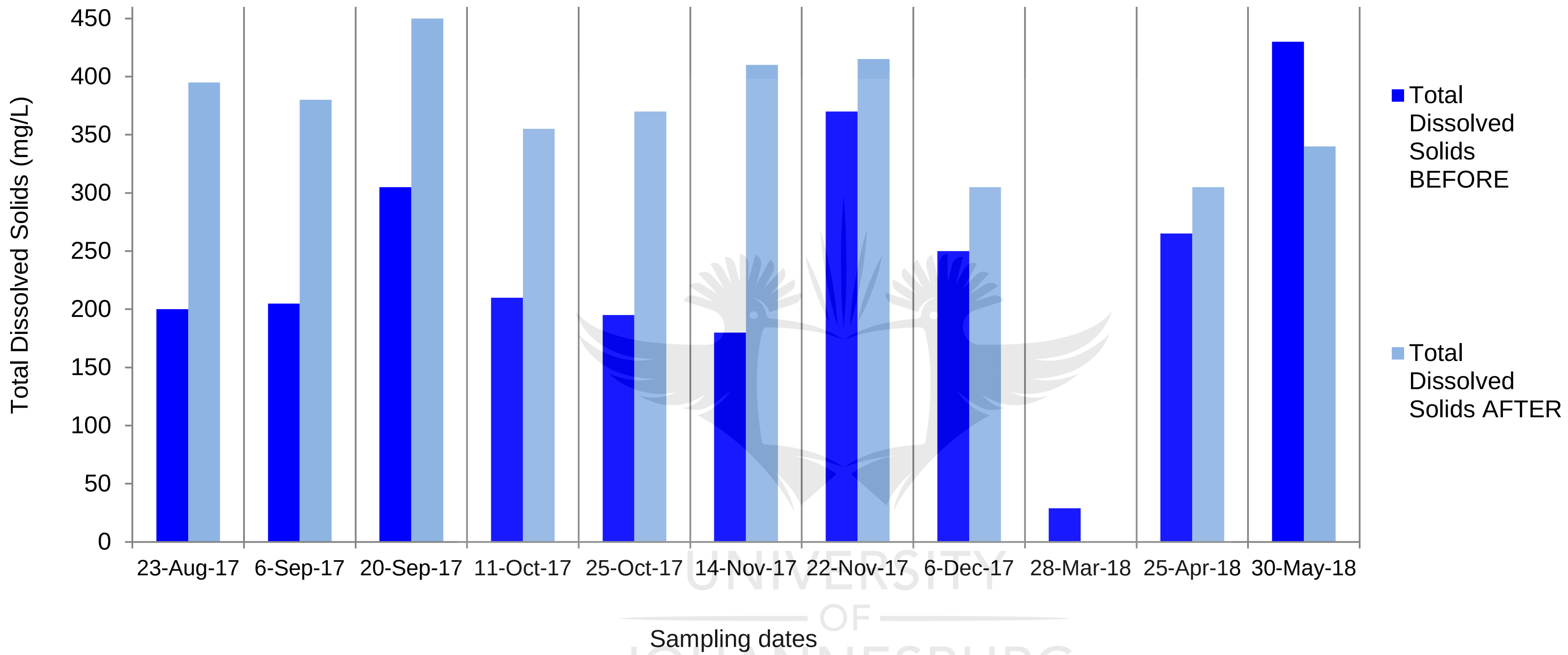

Figure 15. Changes in TDS (mg/L) over time in greywater, before and after treatment by the MO-AW.

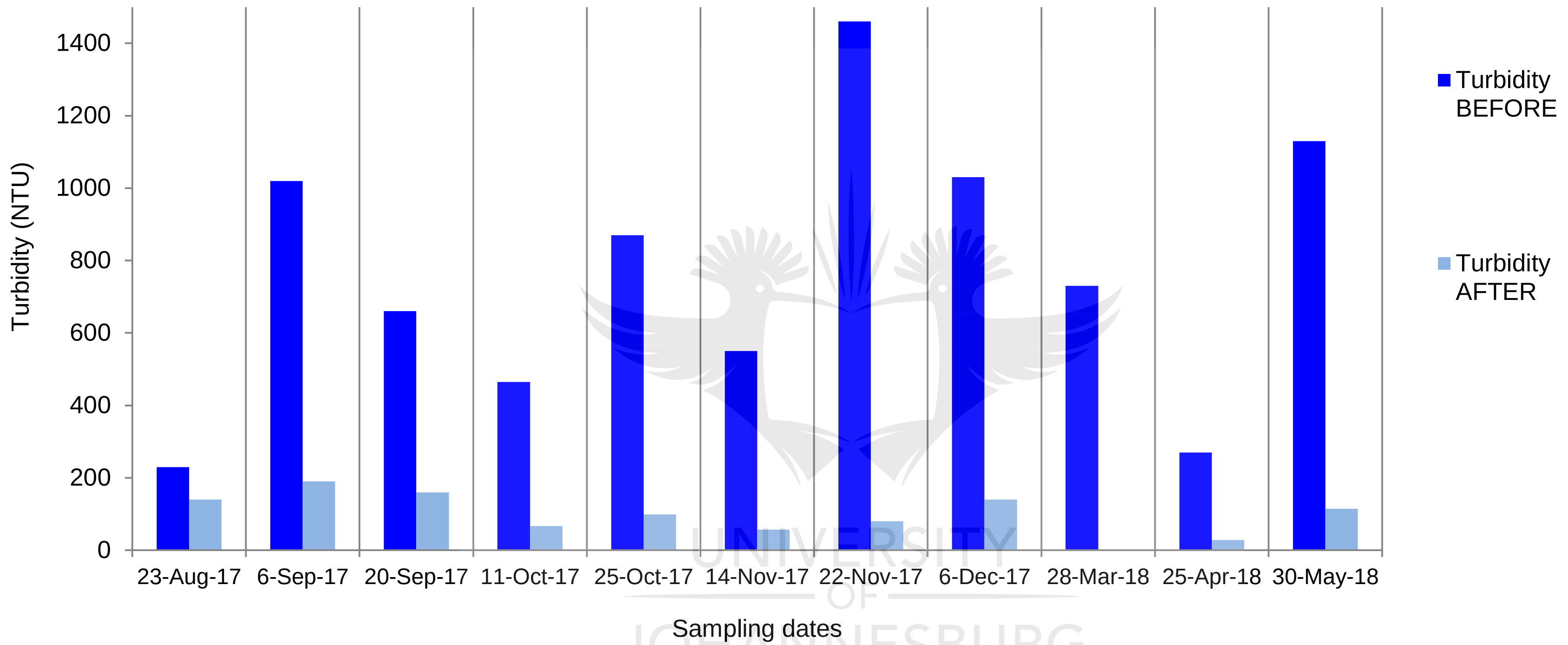

Figure 16. Changes in turbidity (NTU) over time in greywater, before and after treatment by the MO-AW.

4.3.2. Water anion parameters analysis

Table 13. Anion values before and after treatment by the MO-AW, including paired samples t-test results (two-tailed P - and t - values; mean ± SE) (n = 11; d.f. = 10), and applicable TWQR for the WQG/I (DWAF, 1996a). ***Bolded*** *P-values are regarded as significant at the P = 0.05 level.*

Parameter	Before treatment	After treatment	TWQR for WQG/I	Paired *t*-tests		
				P	*t*	Mean difference ± SE
TP (mg/L)	1.45 ± 0.33	0.06 ± 0.02	-	**0.002**	4.28	1.39 ± 0.32
NO_3 (mg/L)	3.84 ± 1.11	2.82 ± 0.88	5	0.55	0.63	1.02 ± 1.69
SO_4 (mg/L)	11.63 ± 1.73	3.92 ± 0.79	-	**0.002**	4.09	7.71 ± 1.88
Cl (mg/L)	40.09 ± 9.48	40.36 ± 6.65	100	0.98	-0.032	-0.27 ± 8.44

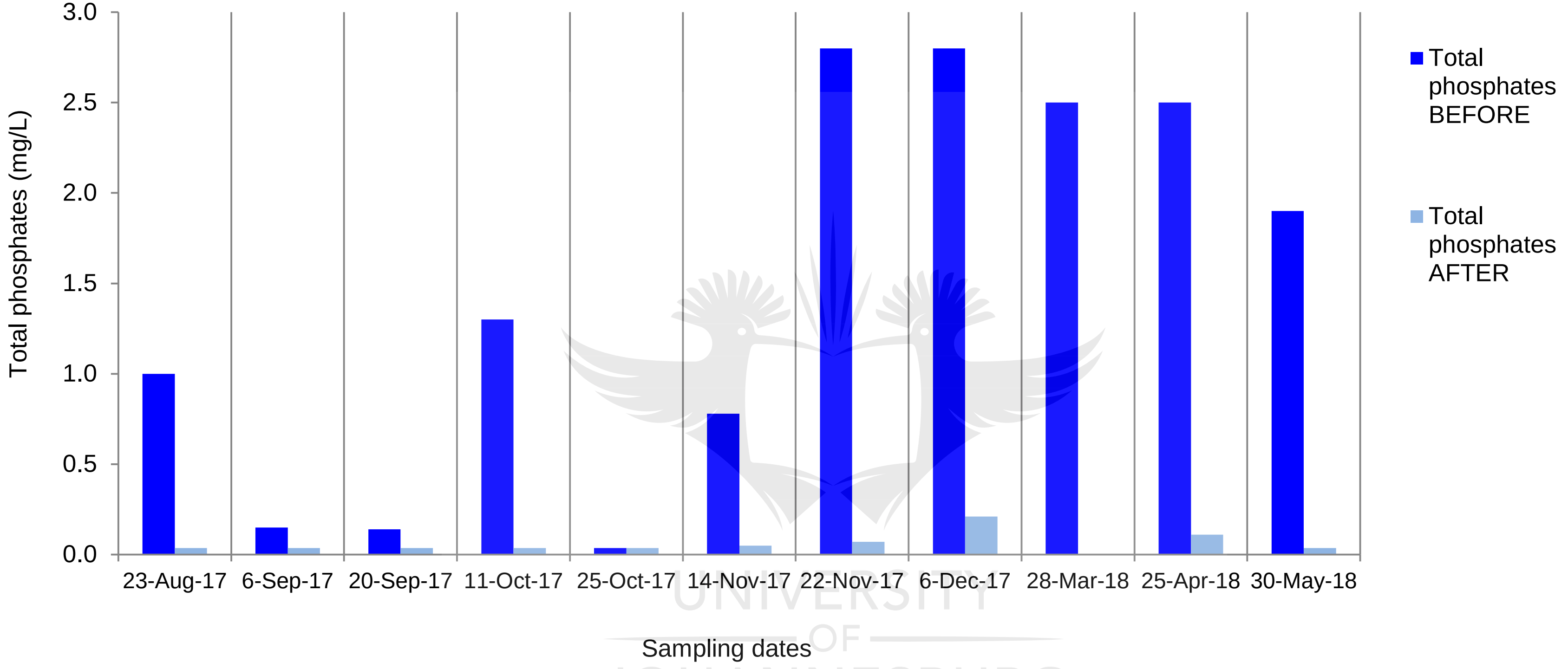

Figure 17. Changes in TP (mg/L) over time in greywater, before and after treatment by the MO-AW.

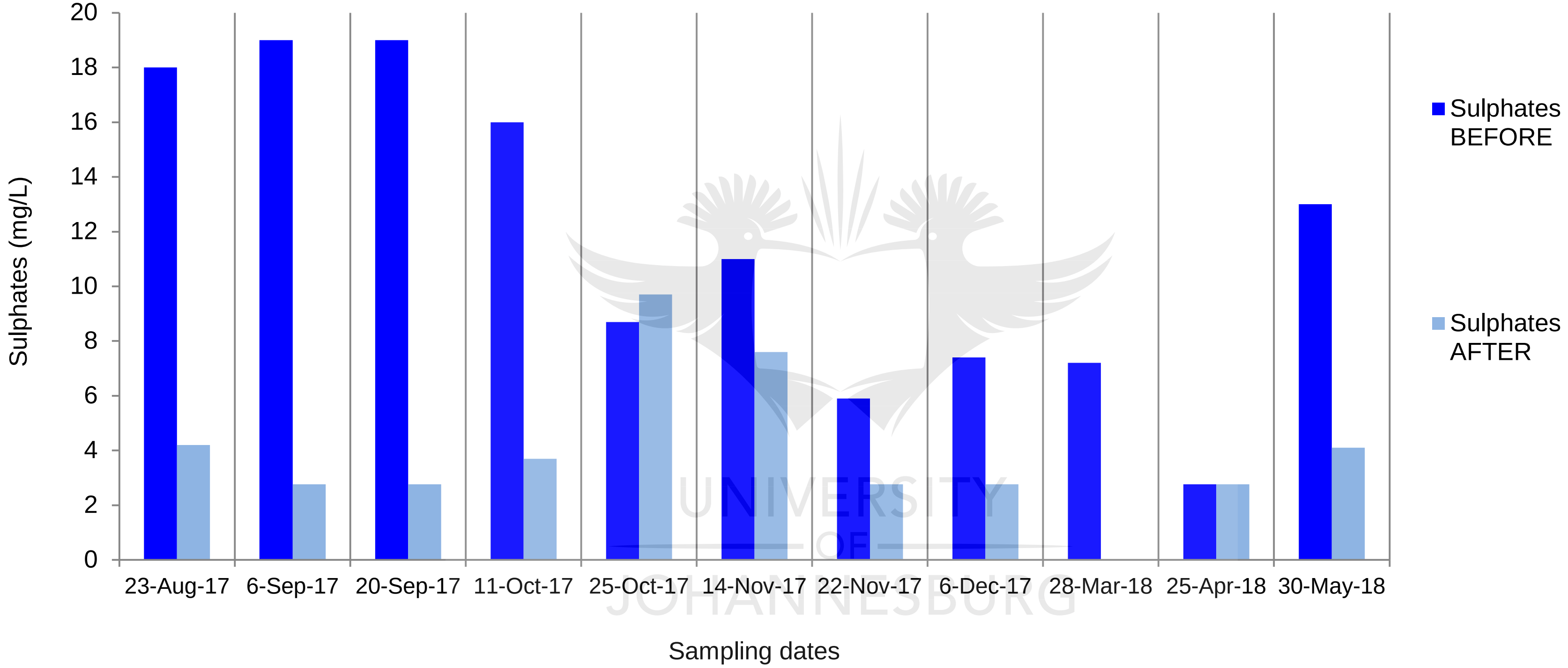

Figure 18. Changes in SO_4 (mg/L) over time in greywater, before and after treatment by the MO-AW.

4.3.3. Water organics parameters analysis

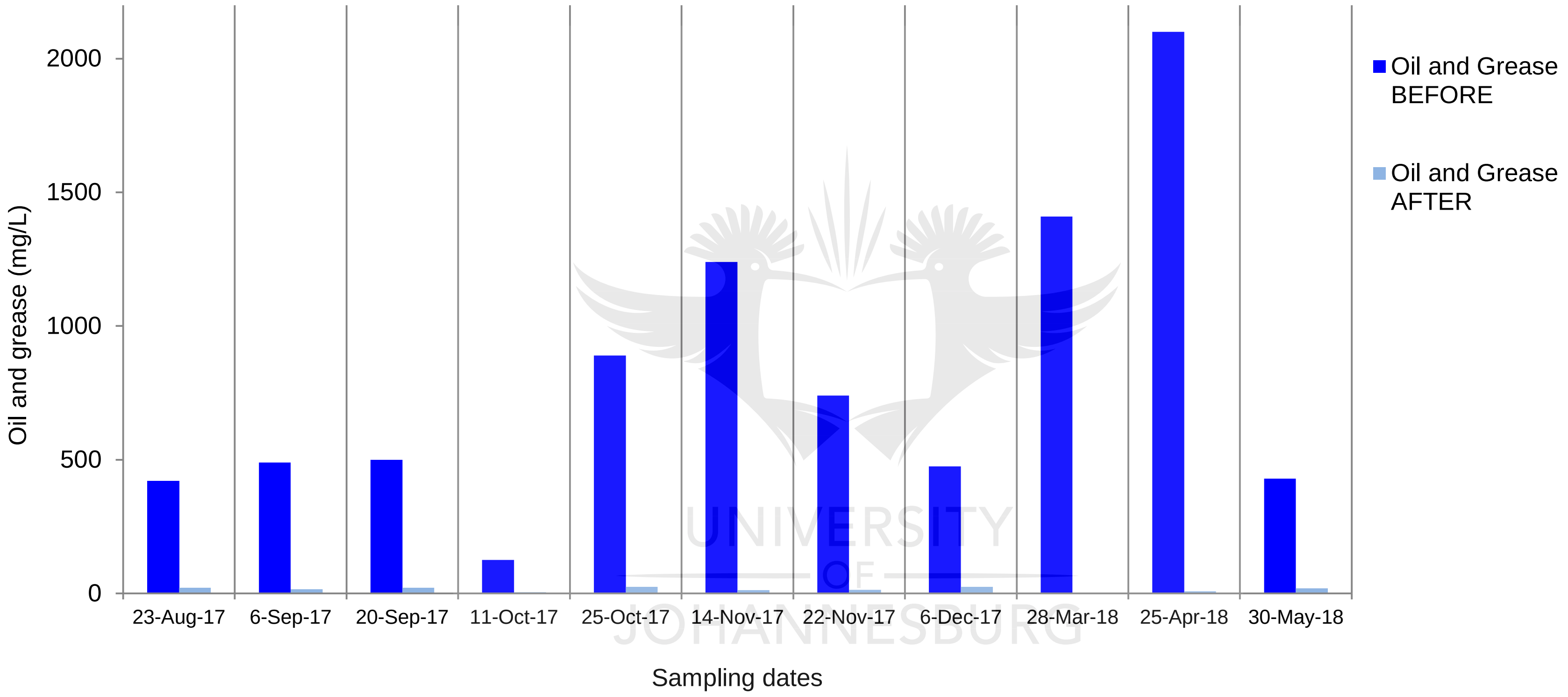

Figure 19. Changes in oil and grease (mg/L) over time in greywater, before and after treatment by the MO-AW.

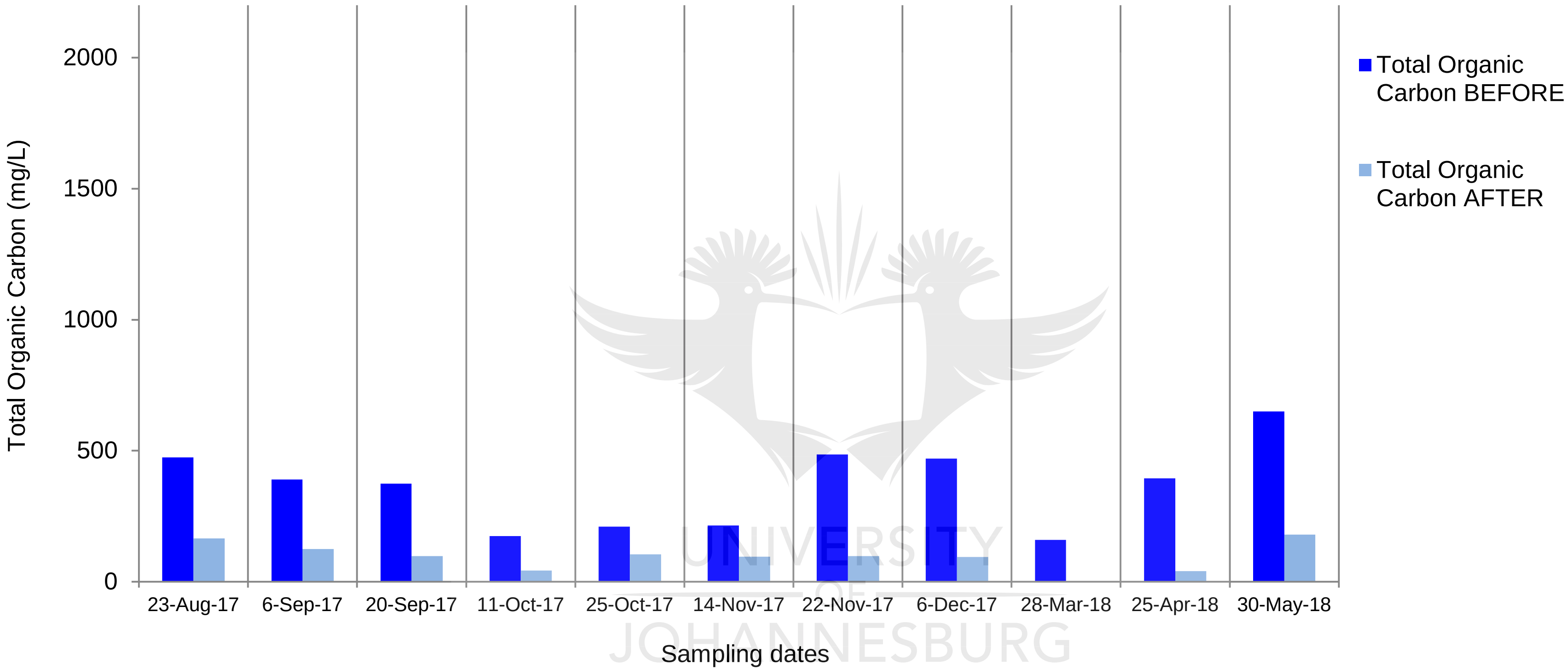

Figure 20. Changes in TOC (mg/L) over time in greywater, before and after treatment by the MO-AW.

4.3.4. Water *E. coli* analysis

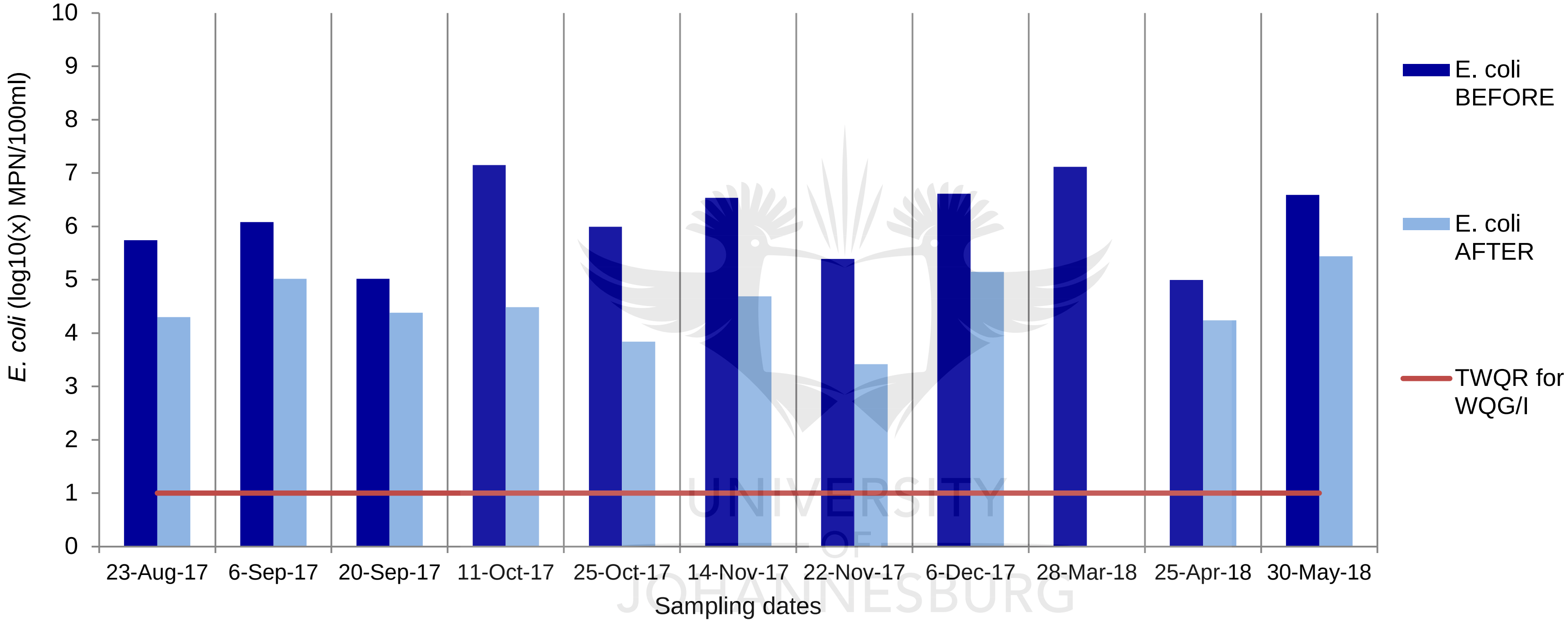

Figure 21. Changes in E. coli (log10(x)) (MPN/100 mL) over time in greywater, before and after treatment by the MO-AW, including the TWQR for the WQG/I (DWAF, 1996a) for E. coli.

Paired samples *t-tests* results for the MO-AW (Figures 17 and, 18, Table 13 and Appendix C) showed a significant difference between pre- and post-treatment for two anions measured. There was a significant decrease in both TP (t = 4.28, P = 0.002, d.f. = 10) (Figure 17) and SO_4 (t = 4.09, P = 0.02, d.f. = 10) (Figure 18) (Table 13). There were no significant differences for any of the other anions measured between pre- and post-treatment of greywater by the MO-AW.

Paired samples *t-tests* (Figures 19 and 20) for comparisons for the MO-AW showed a significant decrease in organics between pre- and post-treatment for oil and grease (t = 4.52, P = 0.01, d.f. = 10) (Figure 19) and TOC (t = 7.16, P < 0.05, d.f. = 10) (Figure 20).

Paired samples *t-tests* (Figure 21) showed a significant decrease in *E. coli* counts (t = 2.44, P = 0.04, d.f. = 10) between pre- and post-treatment greywater for the MO-AW (Figure 21). *Escherichia coli* counts were above the TWQR for the WQG/I (DWAF, 1996a).

Table 14. Water quality metal results (mean ± SE) post-treatment for the MO-AW.

Water Quality Parameter	Unit	Mean ± SE
Ca hardness	mg/L $CaCO_3$	95.18 ± 16.03
Mg hardness	mg/L $CaCO_3$	41.82 ± 5.70
B	µg/L	85.27 ± 14.08
Ca	mg/L	38.18 ± 6.42
K	mg/L	8.68 ± 1.17
Mg	mg/L	10.29 ± 1.34
Na	mg/L	27.62 ± 4.70

There were no significant differences for any of the metals, namely B, Ca, K, Mg, Na, Ca hardness or Mg hardness analysed from the greywater between pre- and post-treatment by the MO-AW (Table 14). There was a slight increase (means ± SE) in the hardness and salt concentration of the water after treatment by the MO-AW, indicated by non-significant increases pre- and post-treatment in Ca hardness (70.18 ± 9.91; 95.18 ± 16.03 mg/L $CaCO_3$, respectively), Mg hardness (35.55 ± 4.51; 41.82 ± 5.69 mg/L $CaCO_3$, respectively), Ca (28.27 ± 4.00; 38.18 ± 6.42 mg/L, respectively), and Mg (8.60 ± 1.10; 10.29 ± 1.34 mg/L, respectively).

There was also a non-significant decrease in the concentrations of B (120.72 ± 19.02; 85.27 ± 14.08 µg/L, respectively), K (11.76 ± 2.92; 8.68 ± 1.17 mg/L, respectively), and Na (29.27 ± 4.30; 30.45 ± 3.93 mg/L, respectively).

The values for both Na and B fell below the TWQR WQG/I (DWAF, 1996a). There are no TWQR for any of the other metals as prescribed by the WQG/I.

4.3.5. Plant health analysis

Table 15. The correlation coefficient values between average temperature per day (°C) and six plant health criteria, for the MO-AW at Zwartkopjes, Rand Water.

Plant health criteria	Correlation coefficient
Leaf health	-0.14
Leaf discolouration	0.21
Plant pests	-
Fungus/diseases	-
Flowers	0.03
Abundance (% of surface area) and height (cm)	0.39

There was no correlation between average temperatures (°C) per day of sampling and any of the plant health criteria over the sampling period for the MO-AW (Table 15).

The plants growing in the MO-AW had an average health rating of 82.95% (Figure 22). No plant pests, diseases or fungus infections were noticed on the plants growing in this wetland over the whole sampling period (Figure 22).

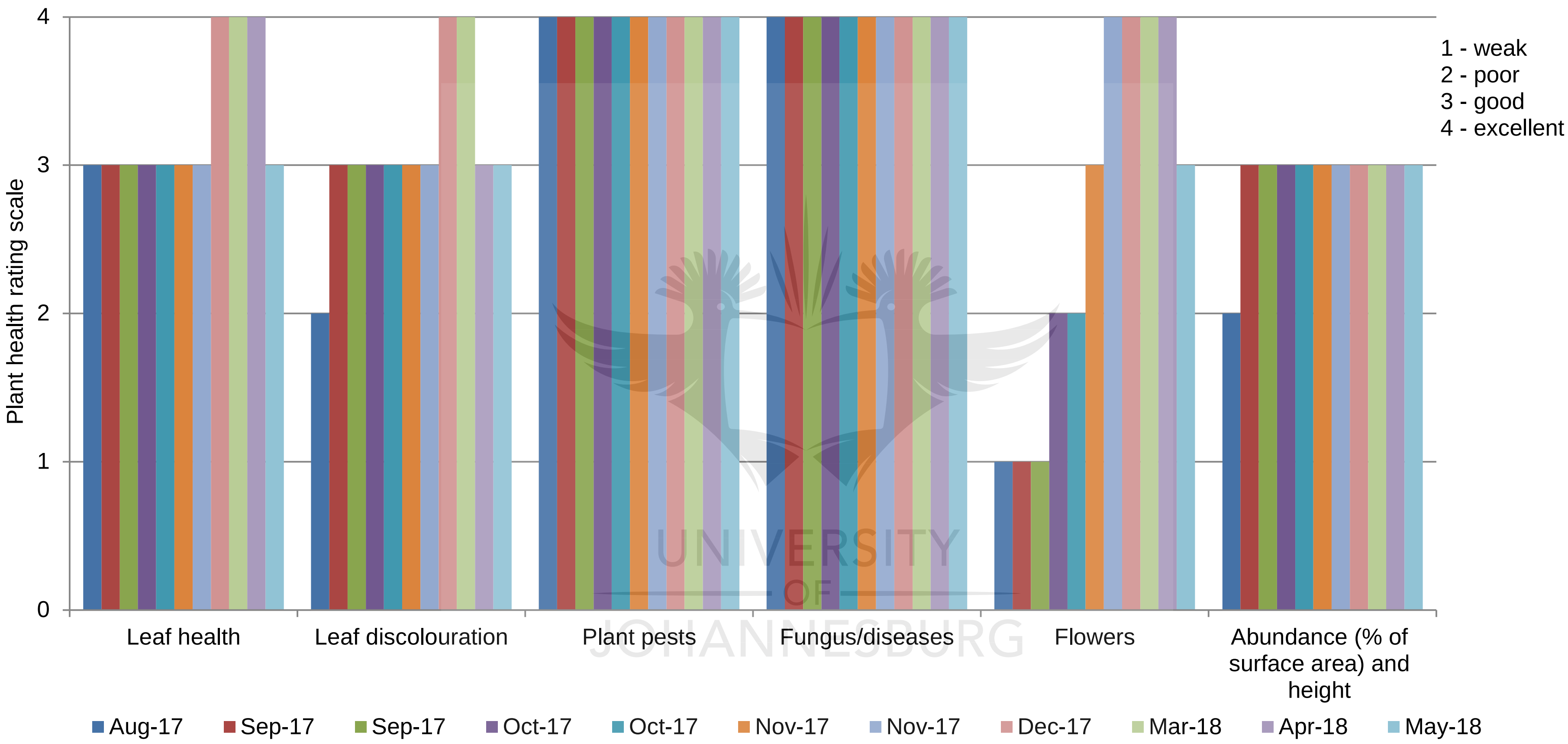

Figure 22. Results of the plant health rating scale to analyse the growth and health patterns of plants growing over the sampling period in the MO-AW, Zwartkopjes, Rand Water.

4.4. Nursery artificial wetland (N-AW)

The greywater treated by the N-AW consisted of kitchen sink, bathroom basin, and shower wastewater. Treatment of the greywater by the CW showed an overall decrease in organics, and certain anions and metals. However, there was an overall increase in the pH and hardness of the greywater post-treatment. There was no significant effect of treatment by the N-AW on the presence of pathogenic organisms, specifically *E. coli*.

4.4.1. Physical water quality parameters analysis

Paired samples *t-test*s were used to compare the differences in twenty-one water quality parameters between pre- and post-treatment for the N-AW (Appendix C). There was a significant difference for five physical water quality parameters, namely an increase in EC (t = 4.23, P = 0.002, d.f. = 10) (Figure 23), alkalinity (t = -3.72, P = 0.004, d.f. = 10) (Figure 24), pH (t = -7.53, P < 0.05, d.f. = 10) (Figure 25),and TDS (t = -4.21, P = 0.002, d.f. = 10) (Figure 26), and a decrease in turbidity (t = 4.42, P = 0.001, d.f. = 10) (Figure 27) (Table 16). There were no significant differences for any of the other physical water quality parameters of the greywater between pre- and post-treatment by the N-AW.

4.4.2. Water anions parameter analysis

Paired samples *t-test*s results for the N-AW (Appendix C) showed a significant decrease between pre- and post-treatment for TP (t = 2.19, P = 0.05, d.f. = 10) only (Table 17) (Figure 28). There were no significant differences for any of the other anions measured between pre- and post-treatment of greywater by the N-AW.

4.4.3. Water organics parameter analysis

Paired samples *t-test*s for comparisons for the N-AW showed a significant decrease between pre- and post-treatment for oil and grease (t = 6.59, P < 0.05, d.f. = 10) (Figure 29) and TOC (t = 5.38, P < 0.05, d.f. = 10) (Figure 30).

*Table 16. Physical water quality parameters before and after treatment by the N-AW, including paired samples t-test results (two-tailed P - and t - values; mean ± SE) (n = 11; d.f. = 10) and applicable TWQR for the WQG/I (DWAF, 1996a). **Bolded** P-values are regarded as significant at the P = 0.05 level.*

Parameter	Before treatment	After treatment	TWQR for WQG/I	Paired *t*-tests		
				P	*t*	Mean difference ± SE
EC (mS/m)	30.91 ± 1.70	44.73 ± 3.21	40	**0.002**	-4.23	-13.82 ± 3.27
Alkalinity (mg/L $CaCO_3$)	92.18 ± 9.69	148.18 ± 8.67	-	**0.004**	-3.72	-56.00 ± 15.05
pH	6.06 ± 0.15	7.11 ± 0.09	6.5-8.4	**<0.05**	-7.53	-1.05 ± 0.14
DO (mg/L)	1.34 ± 0.84	1.35 ± 0.69	-	0.98	-0.03	-0.01 ± 0.28
Temperature (°C)	23.03 ± 1.03	22.79 ± 1.03	-	0.42	0.84	0.24 ± 0.28
TDS (mg/L)	189.91 ± 18.93	265.82 ± 28.31	-	**0.002**	-4.21	-75.9 ± 18.01
Turbidity (NTU)	722.27 ± 114.56	136.73 ± 29.81	-	**0.001**	4.42	585.55 ± 132.47

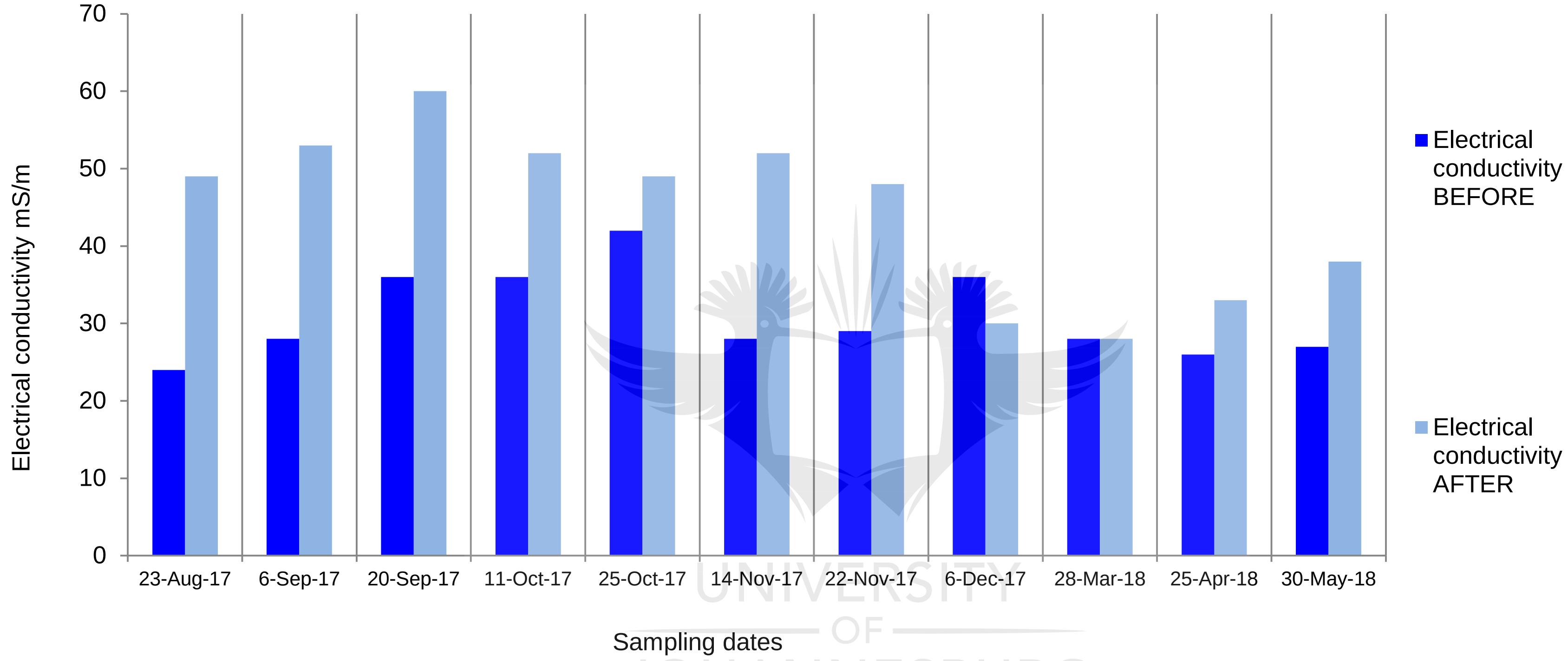

Figure 23. Changes in EC (mS/m) over time in greywater, before and after treatment by the N-AW.

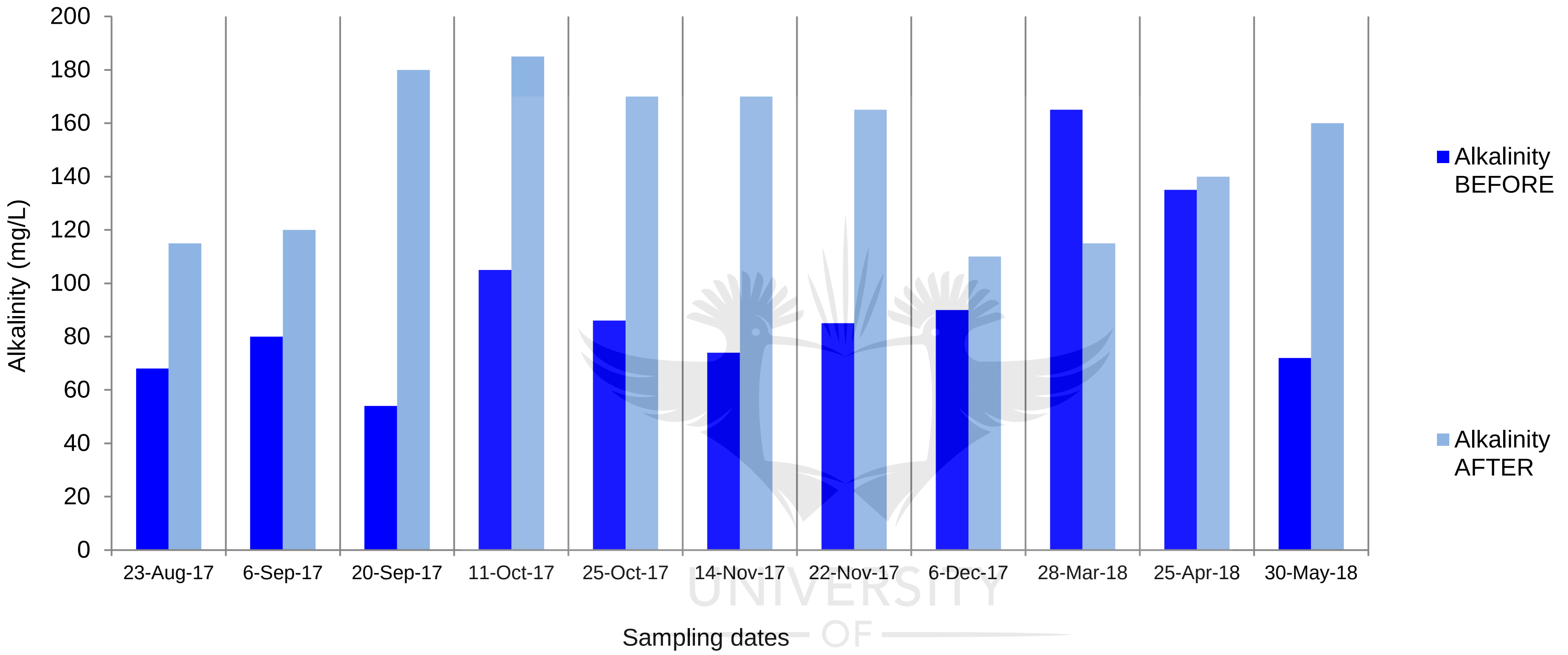

Figure 24. Changes in alkalinity (mg/L) over time in greywater, before and after treatment by the N-AW.

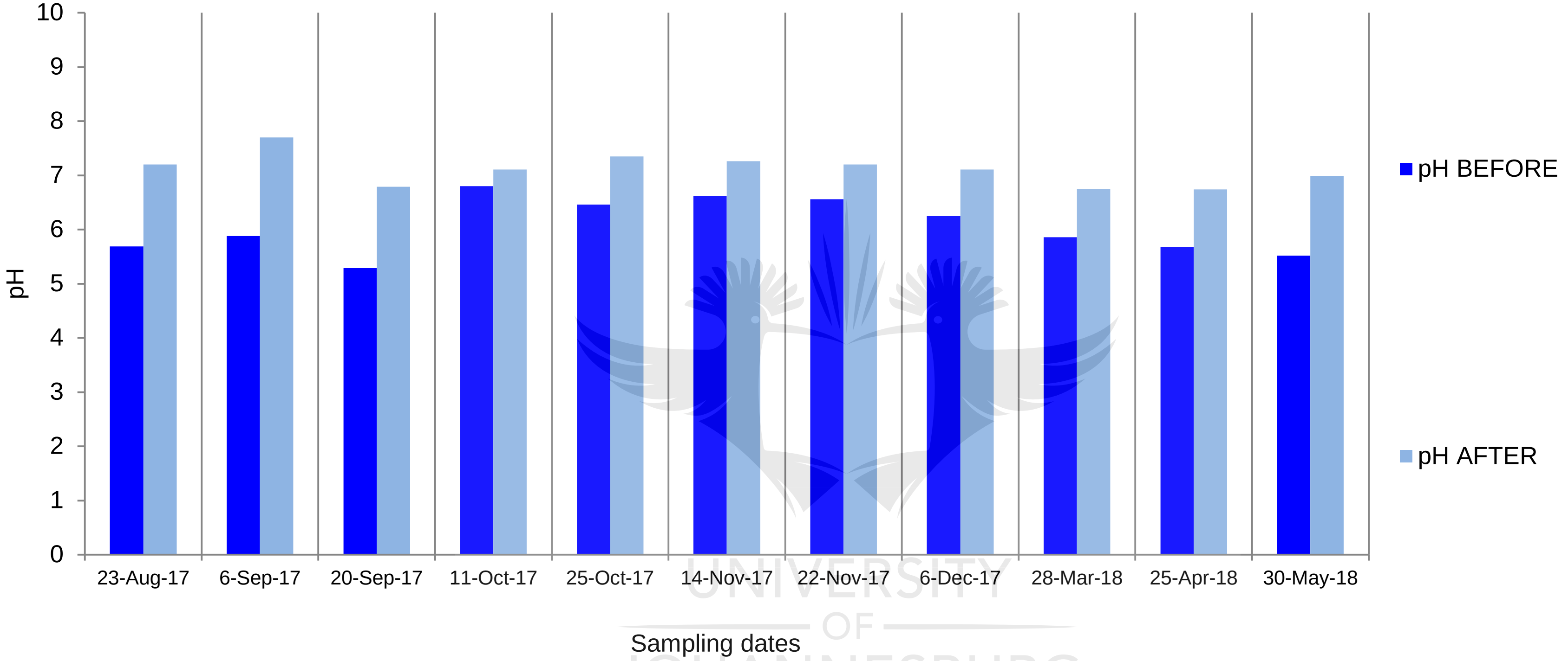

Figure 25. Changes in pH over time in greywater, before and after treatment by the N-AW.

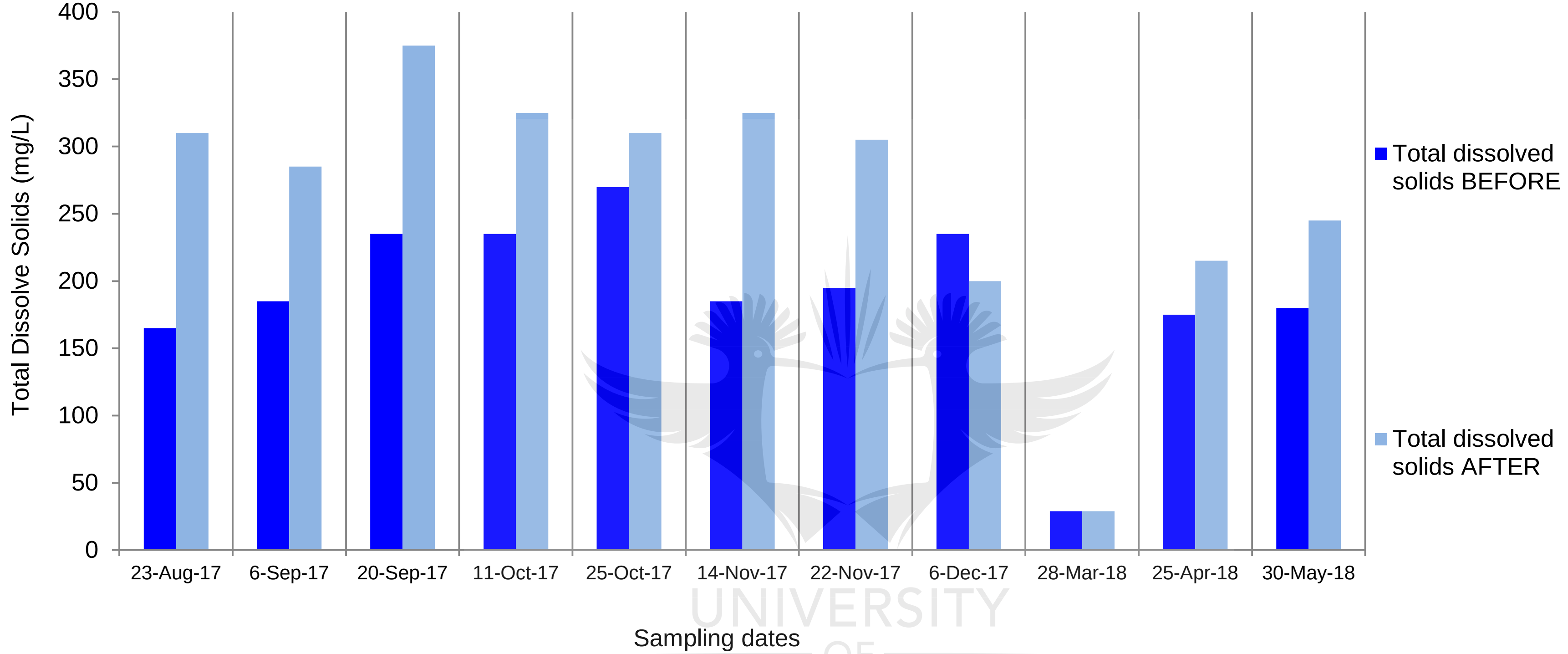

Figure 26. Changes in TDS (mg/L) over time in greywater, before and after treatment by the N-AW.

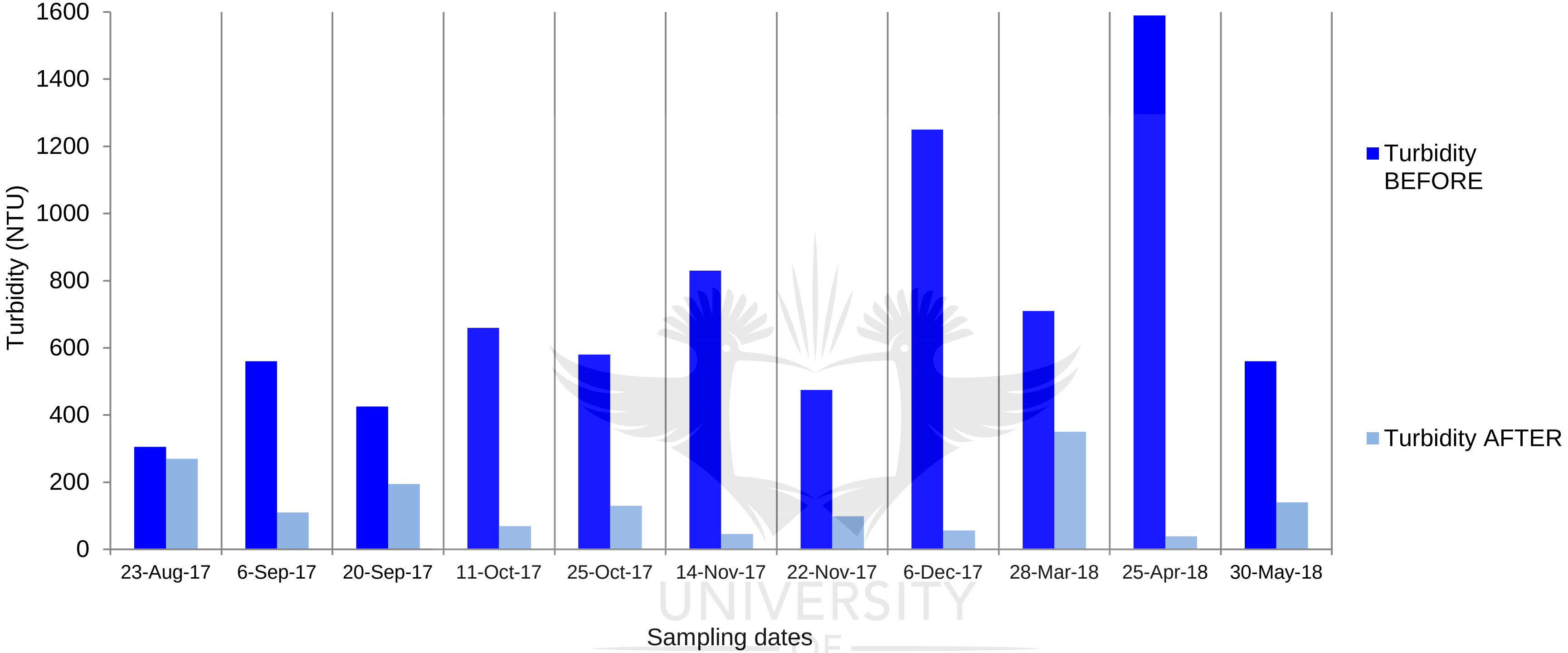

Figure 27. Changes in turbidity (NTU) over time in greywater, before and after treatment by the N-AW.

Table 17. Anion values before and after treatment by the N-AW, including paired samples t-test results (two-tailed P - and t - values; mean ± SE) (n = 11; d.f. = 10), and applicable TWQR for the WQG/I (DWAF, 1996a). ***Bolded*** *P-values are regarded as significant at the P = 0.05 level.*

Parameter	**Before treatment**	**After treatment**	**TWQR for WQG/I**	**Paired *t*-tests**		
				P	*t*	Mean difference ± SE
TP (mg/L)	0.39 ± 0.15	0.06 ± 0.01	-	**0.05**	2.19	0.33 ± 0.15
NO_3 (mg/L)	1.49 ± 0.35	0.82 ± 0.38	5	0.22	1.30	0.67 ± 0.51
SO_4 (mg/L)	11.19 ± 2.31	34.56 ± 13.38	-	0.11	-1.78	-23.38 ± 13.1
Cl (mg/L)	29.91 ± 3.10	31.00 ± 4.97	100	0.85	-0.19	-1.09 ± 5.57

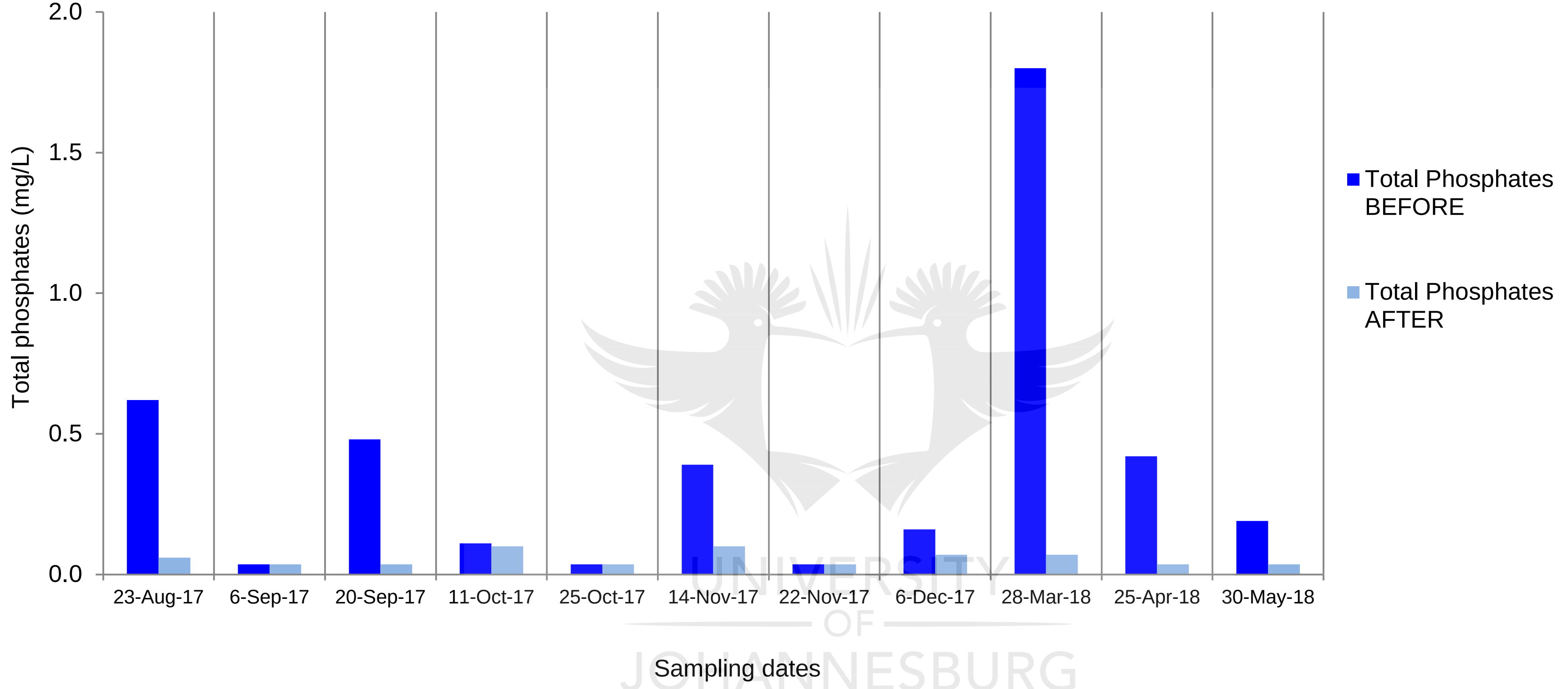

Figure 28. Changes in TP (mg/L) over time in greywater, before and after treatment by the N-AW.

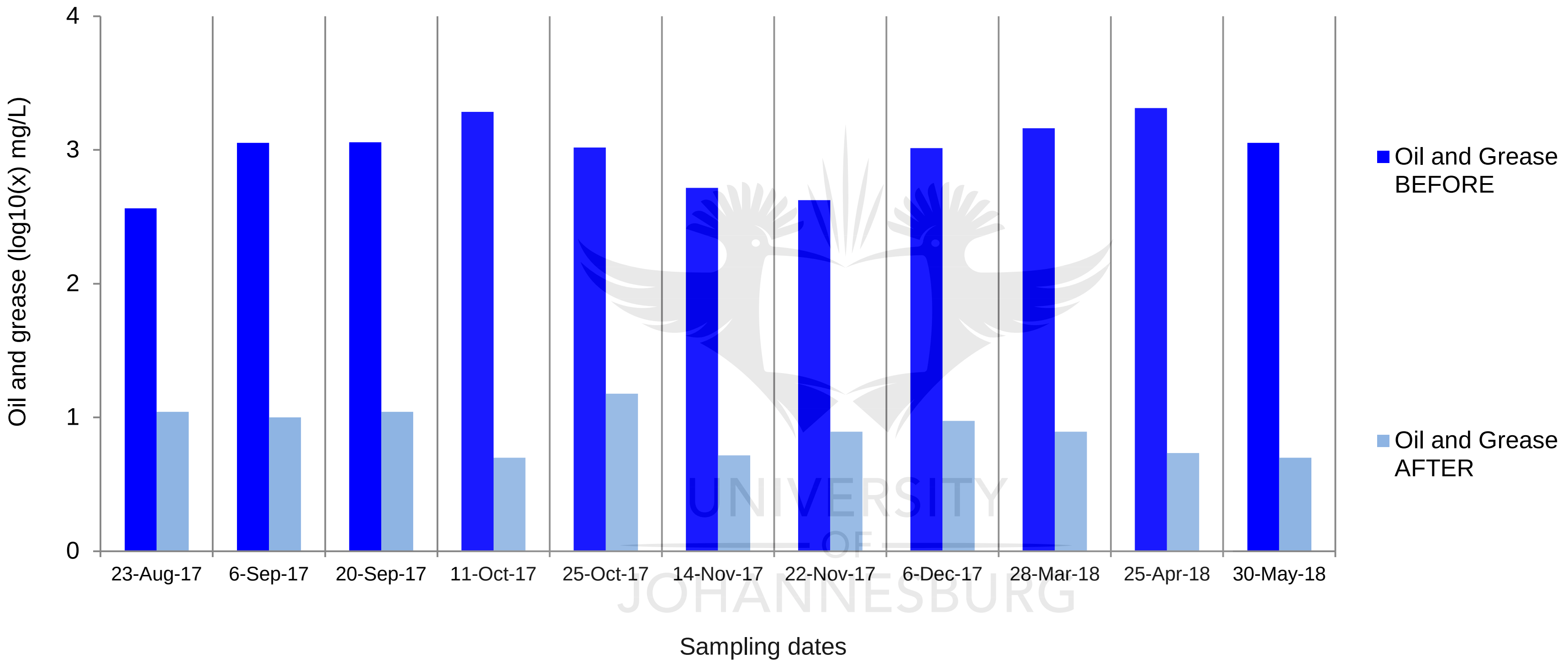

Figure 29. Changes in oil and grease (log10(x)) (mg/L) over time in greywater, before and after treatment by the N-AW.

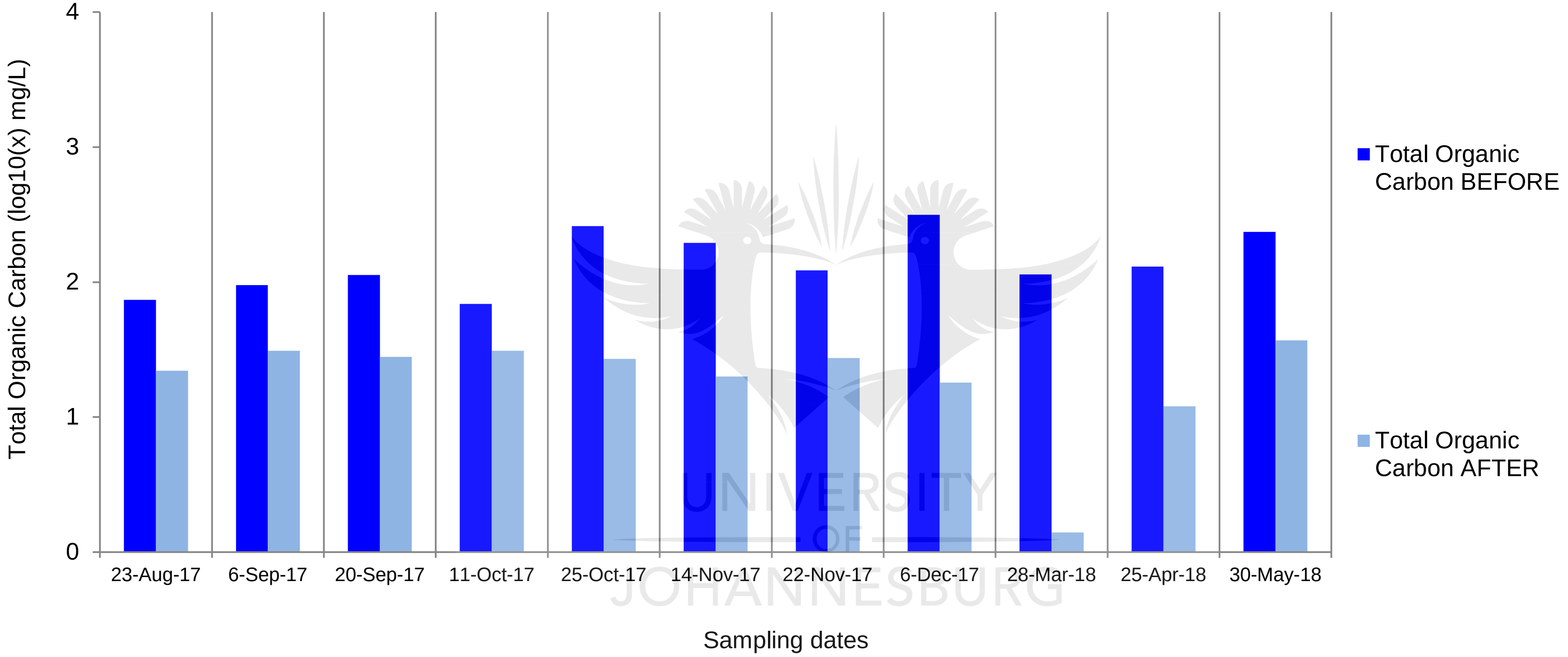

Figure 30. Changes in TOC (log10(x)) (mg/L) over time in greywater, before and after treatment by the N-AW.

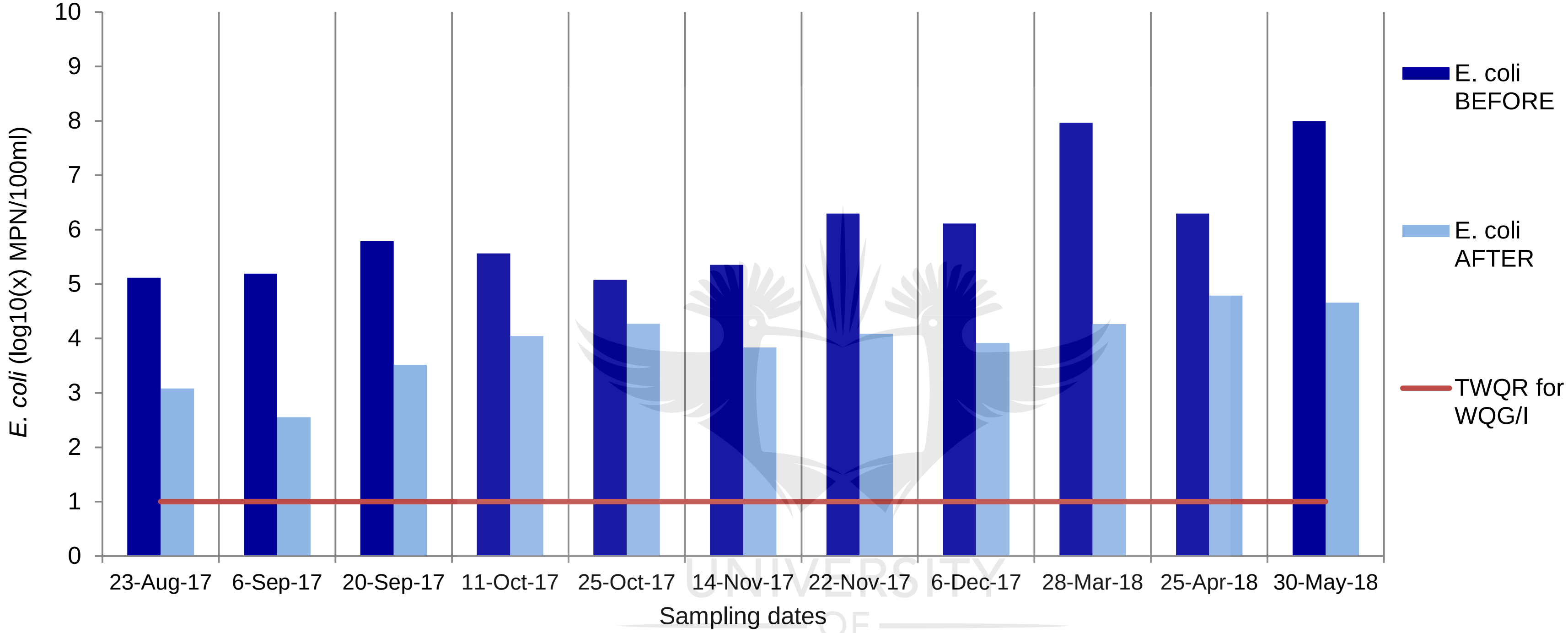

Figure 31. Changes in E. coli (log10(x)) (MPN/100mL) over time in greywater, before and after treatment by the N-AW including the TWQR for the WQG/I (DWAF, 1996a) for E. coli.

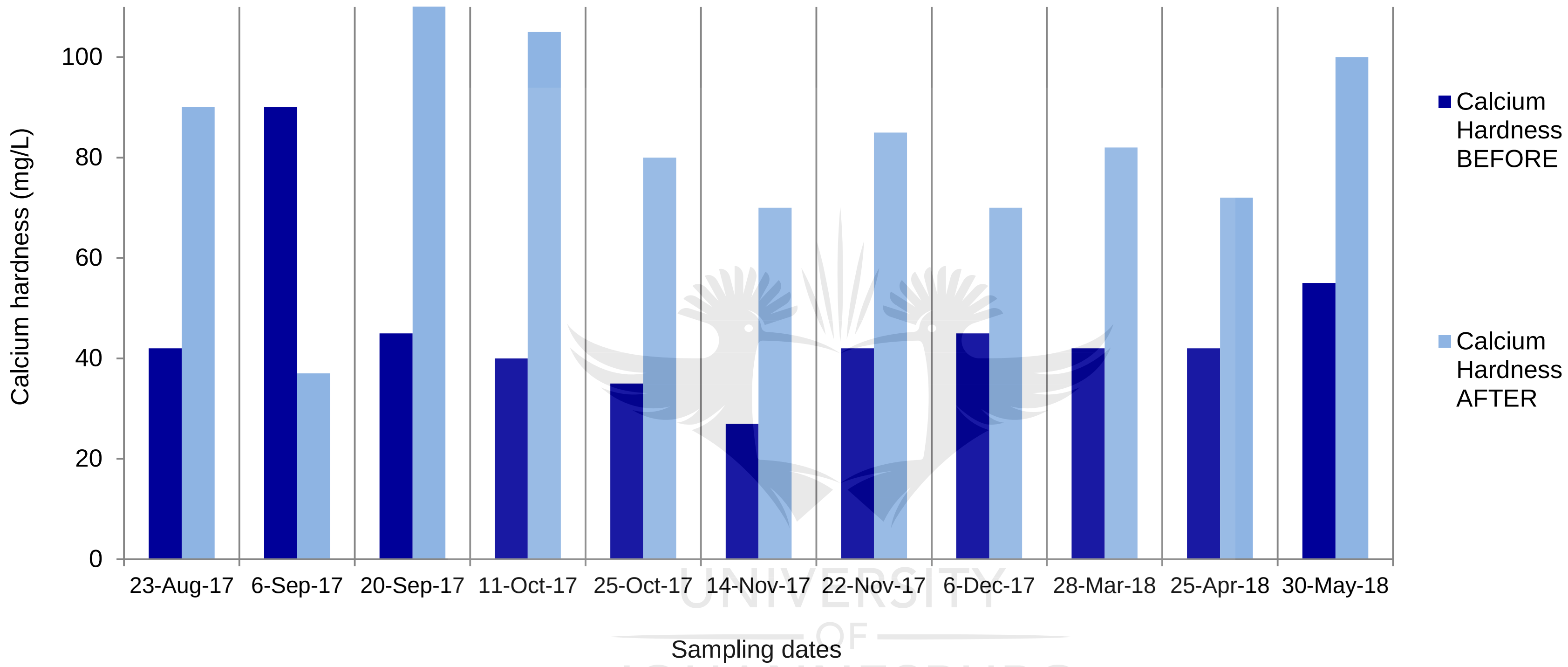

Figure 32. Changes in Ca hardness (mg/L) over time in greywater, before and after treatment by the N-AW.

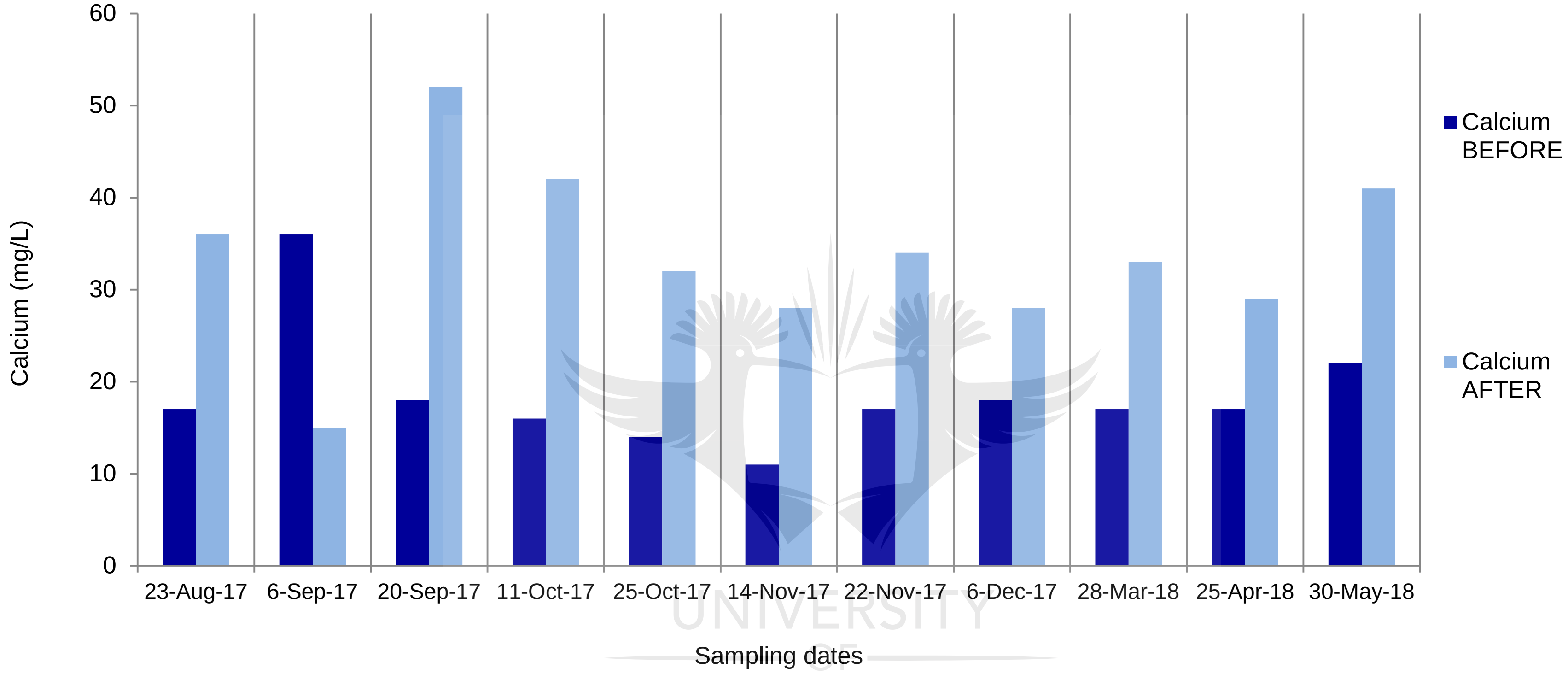

Figure 33. Changes in Ca (mg/L) over time in greywater, before and after treatment by the N-AW.

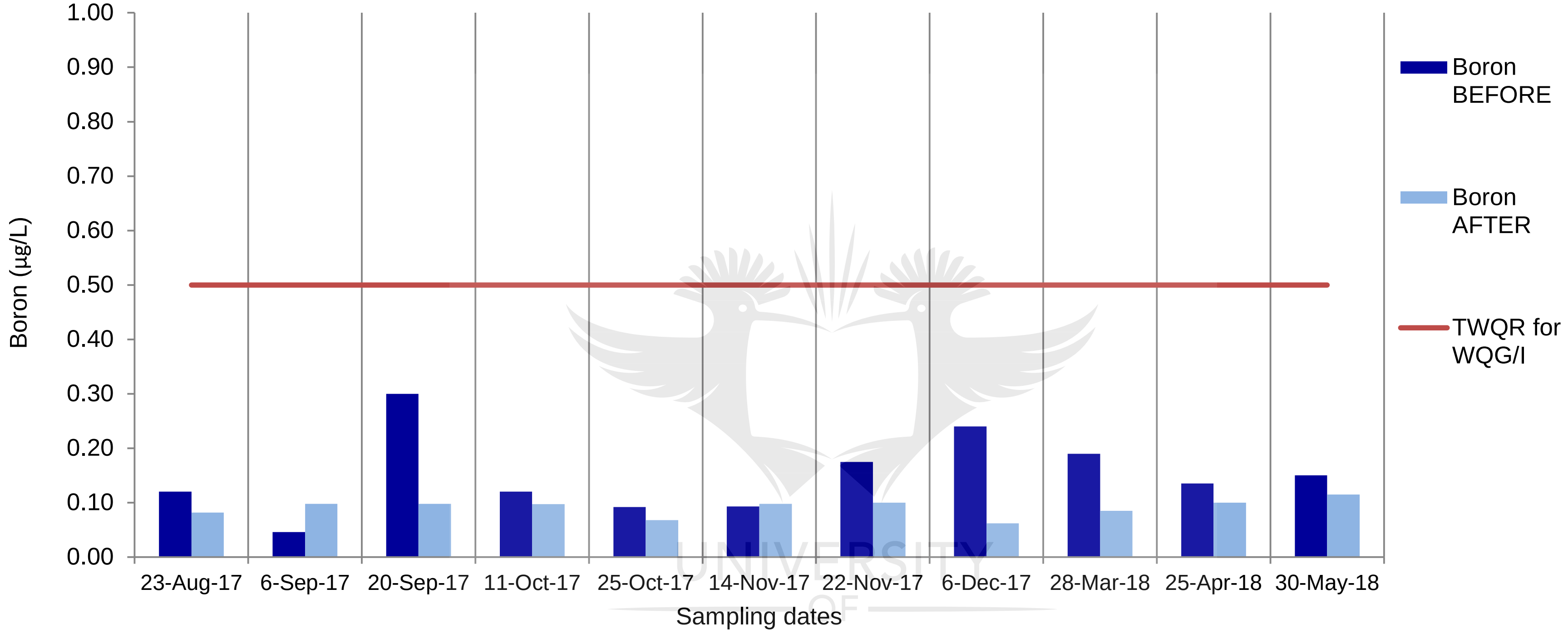

Figure 34. Changes in B (µg/L) over time in greywater, before and after treatment by the N-AW including the TWQR for the WQG/I (DWAF, 1996a) for B.

4.4.4. Water *E. coli* analysis

Paired samples *t-tests* showed no significant change in *E. coli* counts (t = 1.56, P = 0.15, d.f. = 10) between pre- and post-treatment greywater for the N-AW (Figure 31). *Escherichia coli* counts were well above the TWQR as prescribed by the WQG/I (DWAF, 1996a)

4.4.5. Water metal parameter analysis

Paired samples *t-tests* showed a significant increase in Ca hardness (t = -3.67, P = 0.004, d.f. = 10) between pre- and post-treatment greywater for the N-AW (Figure 32).

Paired samples *t*-tests showed a significant increase in Ca (t = -3.67, P = 0.004, d.f. = 10) between pre- and post-treatment greywater for the N-AW (Figure 33).

Table 18. Water quality metal results (mean ± SE) post-treatment for the N-AW.

Water Quality Parameter	Unit	Mean ± SE
Ca hardness	mg/L $CaCO_3$	83.73 ± 7.14
Mg hardness	mg/L $CaCO_3$	44.73 ± 5.10
B	µg/L	91.18 ± 4.68
Ca	mg/L	33.64 ± 2.86
K	mg/L	5.86 ± 0.73
Mg	mg/L	10.25 ± 0.85
Na	mg/L	28.73 ± 3.07

Paired samples *t-tests* showed a significant decrease in B (t = 2.62, P = 0.03, d.f. = 10) between pre- and post-treatment greywater for the N-AW (Figure 34). There were no significant differences for any of the other metals (Table 18). There was a slight increase (means ± SE) in Mg hardness (33.91 ± 2.57; 85.27 ± 5.09 mg/L $CaCO_3$, respectively), DO (1.34 ± 0.84; 1.35 ± 0.69 mg/L O_2, respectively), SO_4 (11.19 ± 2.31; 34.56 ± 13.38 mg/L, respectively), and Mg (8.25 ± 0.63; 10.25 ± 0.85 mg/L, respectively). There was no change (means ± SE) in K pre-treatment (5.84 ± 0.56 mg/L) and post-treatment (5.86 ± 0.73 mg/L) and Na concentration pre-treatment (40.09 ± 9.57 mg/L) and post-treatment (40.36 ± 6.65 mg/L) by the N-AW. Sodium (Na) and B concentrations were below the TWQR as prescribed by the WQG/I (DWAF, 1996a).

4.4.6. Plant health analysis

Table 19. The correlation coefficient values between average temperature per day (°C) and six plant health criteria, for the N-AW at Zwartkopjes, Rand Water.

Plant health criteria	Correlation coefficient
Leaf health	-0.02
Leaf discolouration	0.02
Plant pests	-
Fungus/diseases	-
Flowers	0.20
Abundance (% of surface area) and height (cm)	-0.16

There was no correlation between average temperatures (°C) per day of sampling and any of the plant health criteria over the sampling period for the N-AW (Table 19).

The plants growing in the N-AW had an average health rating of 81.06%, the lowest rating of the three wetlands. No plant pests, diseases or fungus infections were noticed on the plants growing in this wetland over the whole sampling period (Figure 35).

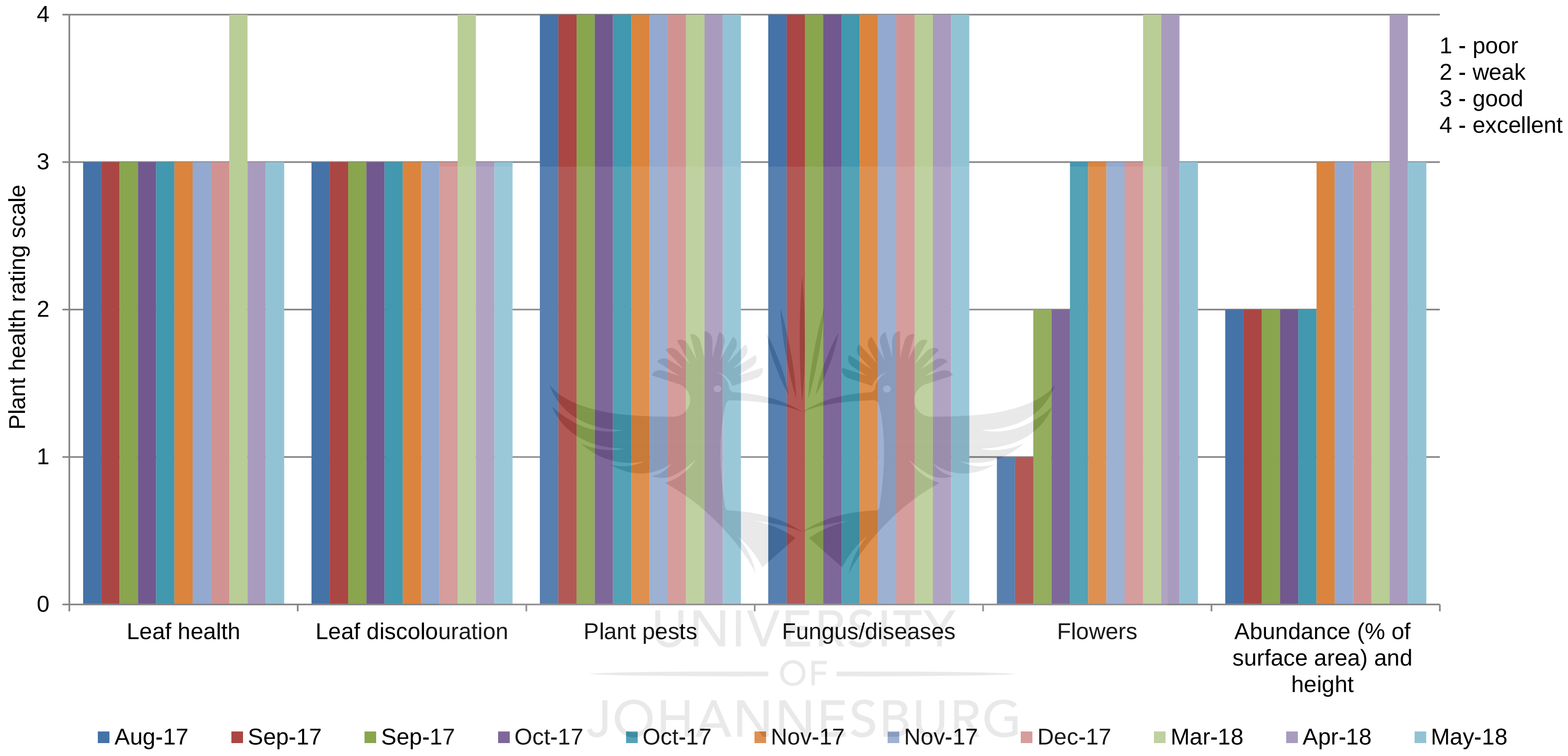

Figure 35. Results of the plant health rating scale to analyse the growth and health patterns of plants growing over the sampling period in the N-AW, Zwartkopjes, Rand Water.

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4.5. Zwartkopjes artificial wetland (Z-AW)

The treatment of shower and bathroom basin greywater by the Z-AW showed no significant effect on the presence of metals, pathogens, or anions in the water.

4.5.1. Physical water quality parameters analysis

Paired samples *t*-tests were used to compare the differences in twenty-one water quality parameters between pre- and post-treatment for the Z-AW (Appendix C). Only one physical water quality parameter showed a significant difference before and after treatment, namely an increase in DO (t = -4.90, P = 0.001, d.f. = 10) (Table 20) (Figure 36). There were no significant differences for any of the other physical water quality parameters of the greywater between pre- and post-treatment by the Z-AW.

4.5.2. Water anions parameter analysis

Paired samples *t*-tests results for the Z-AW (Appendix C**)** showed no significant differences for any of the anions measured between pre- and post-treatment of greywater (Table 21).

4.5.3. Water organics parameter analysis

Paired samples *t*-tests for comparisons of greywater before and after treatment by the Z-AW showed a significant decrease in TOC (t = 3.38, P = 0.007, d.f. = 10) (Figure 37). There was no significant change in oil and grease pre- and post-treatment (Figure 38).

4.5.4. Water *E. coli* analysis

Paired samples *t*-tests showed no significant change in *E. coli* counts (t = 1.63, P = 0.13, d.f. = 10) between pre- and post-treatment greywater for the Z-AW (Figure 39).

Table 20. Physical water quality parameters before and after treatment by the Z-AW, including paired samples t - test results (two-tailed P - and t - values; mean ± SE) (n = 11; d.f. = 10) and applicable TWQR for the WQG/I (DWAF, 1996a). ***Bolded*** *P - values are regarded as significant at the P = 0.05 level.*

Parameter	Before treatment	After treatment	TWQR for WQG/I	Paired *t*-tests		
				P	*t*	Mean difference ± SE
EC (mS/m)	44.27 ± 7.84	42.50 ± 5.38	40	0.84	0.21	1.77 ± 8.56
Alkalinity (mg/L $CaCO_3$)	148.73 ± 277.06	122.82 ± 16.92	-	0.48	0.74	25.91 ± 34.88
pH	5.73 ± 0.86	7.33 ± 0.11	6.5 - 8.4	0.10	-1.80	-1.60 ± 0.89
DO (mg/L)	1.15 ± 0.56	2.82 ± 0.78	-	**0.001**	-4.90	-1.67 ± 0.34
Temperature (°C)	19.08 ± 3.00	22.80 ± 1.03	-	0.16	-1.52	-3.72 ± 2.45
TDS (mg/L)	250.82 ± 52.84	266.82 ± 34.21	-	0.74	-0.34	-16.00 ± 48.81
Turbidity (NTU)	140.36 ± 36.02	74.24 ± 68.60	-	0.36	0.96	66.12 ± 68.98

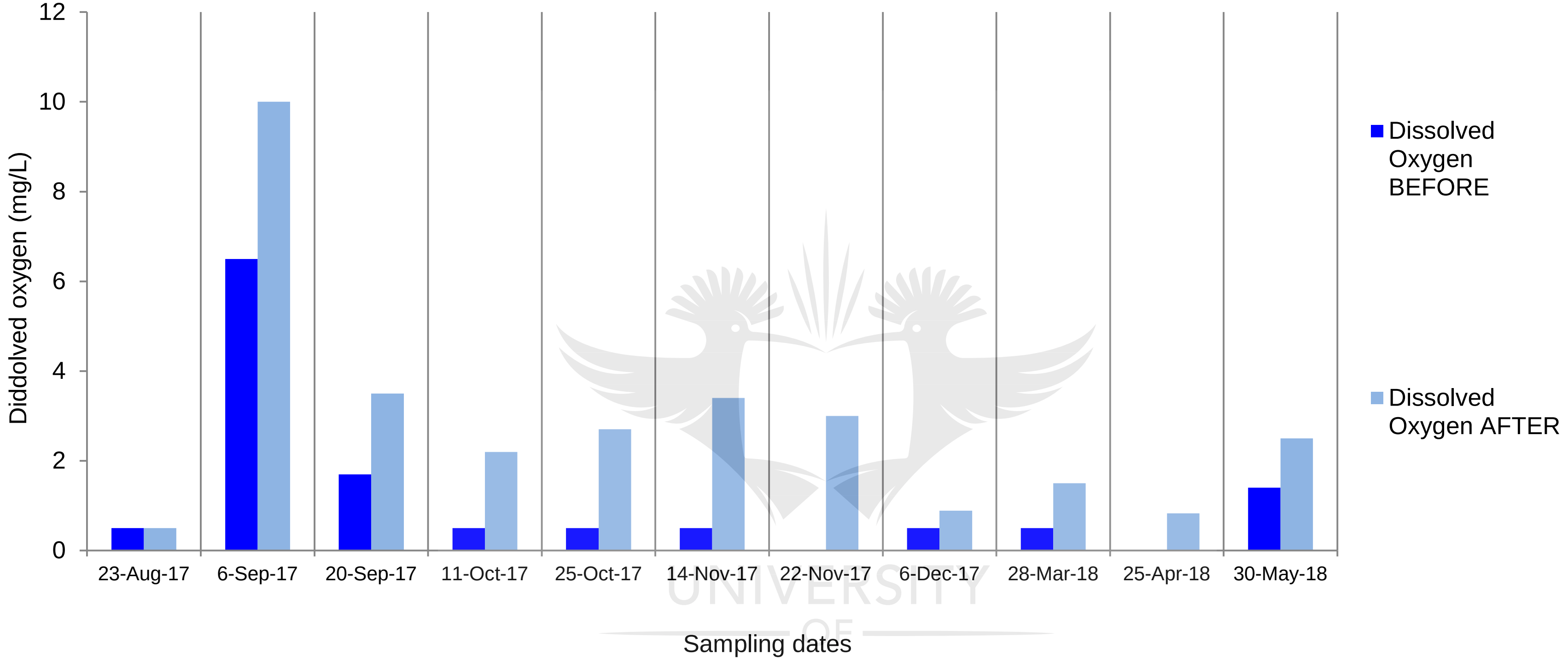


Figure 36. Changes in DO (mg/L) over time in greywater, before and after treatment by the Z-AW.

Table 21. Anion values before and after treatment by the Z-AW, including paired samples t - test results (two-tailed P - and t - values; mean ± SE) (n = 11; d.f. = 10), and applicable TWQR for the WQG/I (DWAF, 1996a).

Parameter	Before treatment	After treatment	TWQR for WQG/I	Paired t-tests		
				P	*t*	Mean difference ± SE
TP (mg/L)	0.04 ± 0.01	0.07 ± 0.01	-	0.06	-2.08	-0.02 ± 0.12
NO_3 (mg/L)	0.37 ± 0.06	0.48 ± 0.03	5	0.09	-1.85	-0.11 ± 0.06
SO_4 (mg/L)	38.50 ± 17.48	72.27 ± 15.50	-	0.09	-1.82	-33.77 ± 18.51
Cl (mg/L)	14.77 ± 5.14	9.45 ± 1.21	100	0.34	1.01	5.33 ± 5.28

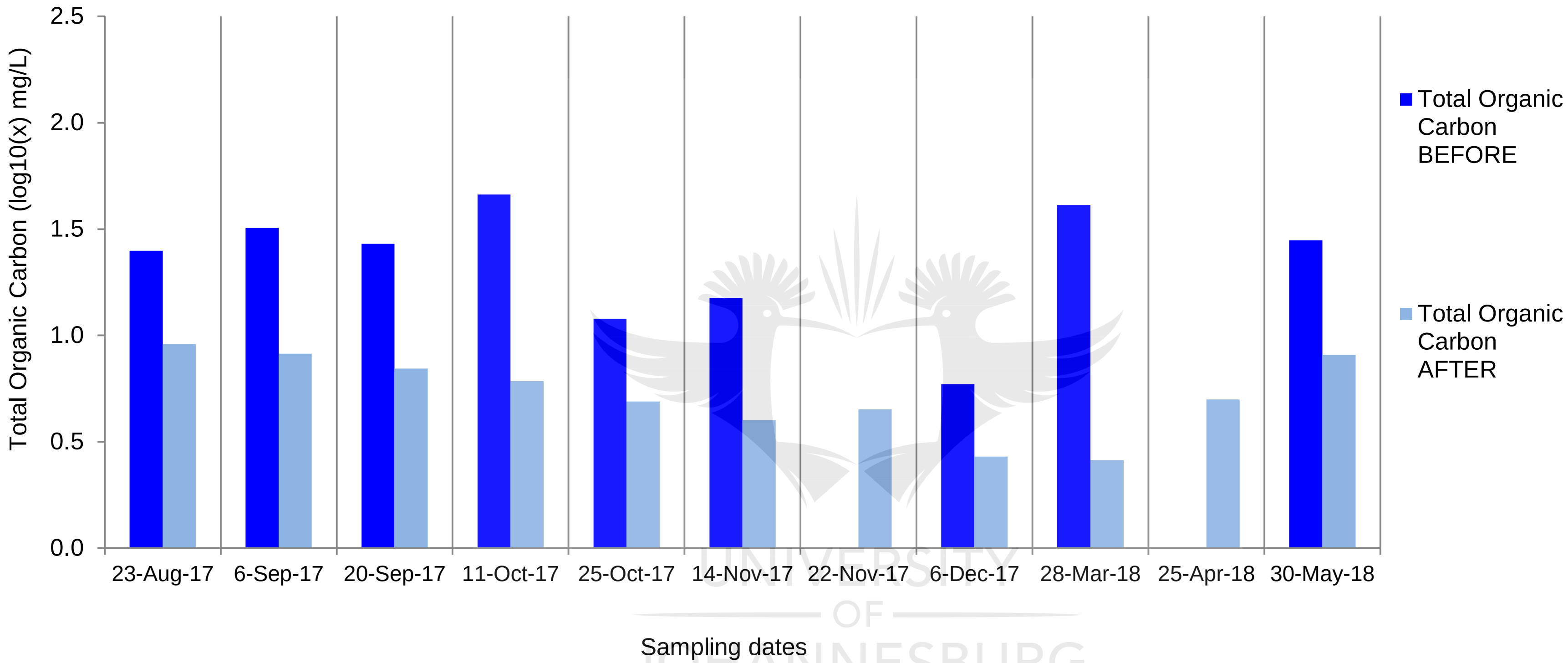


Figure 37. Changes in TOC (log10(x)) (mg/L) over time in greywater, before and after treatment by the Z-AW.

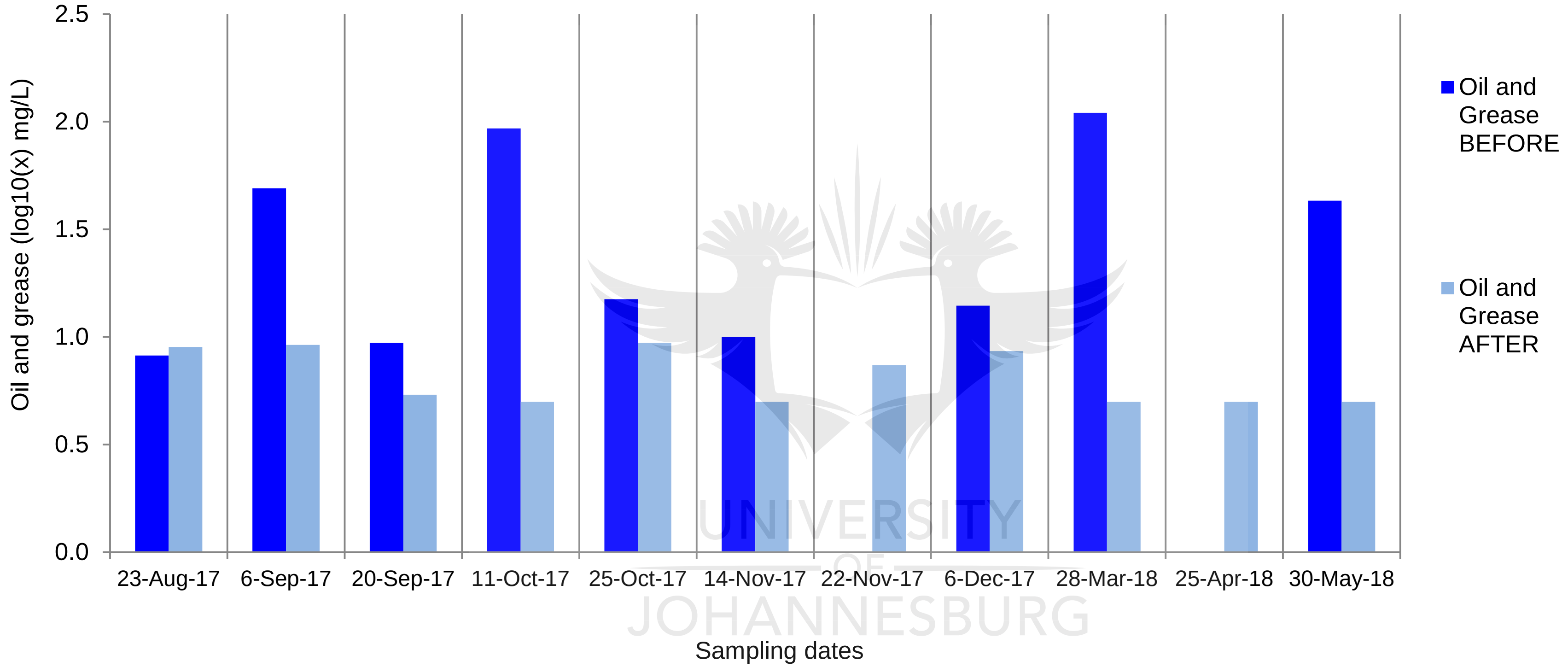


Figure 38. Changes in oil and grease (log10(x)) (mg/L) over time in greywater, before and after treatment by the Z-AW.

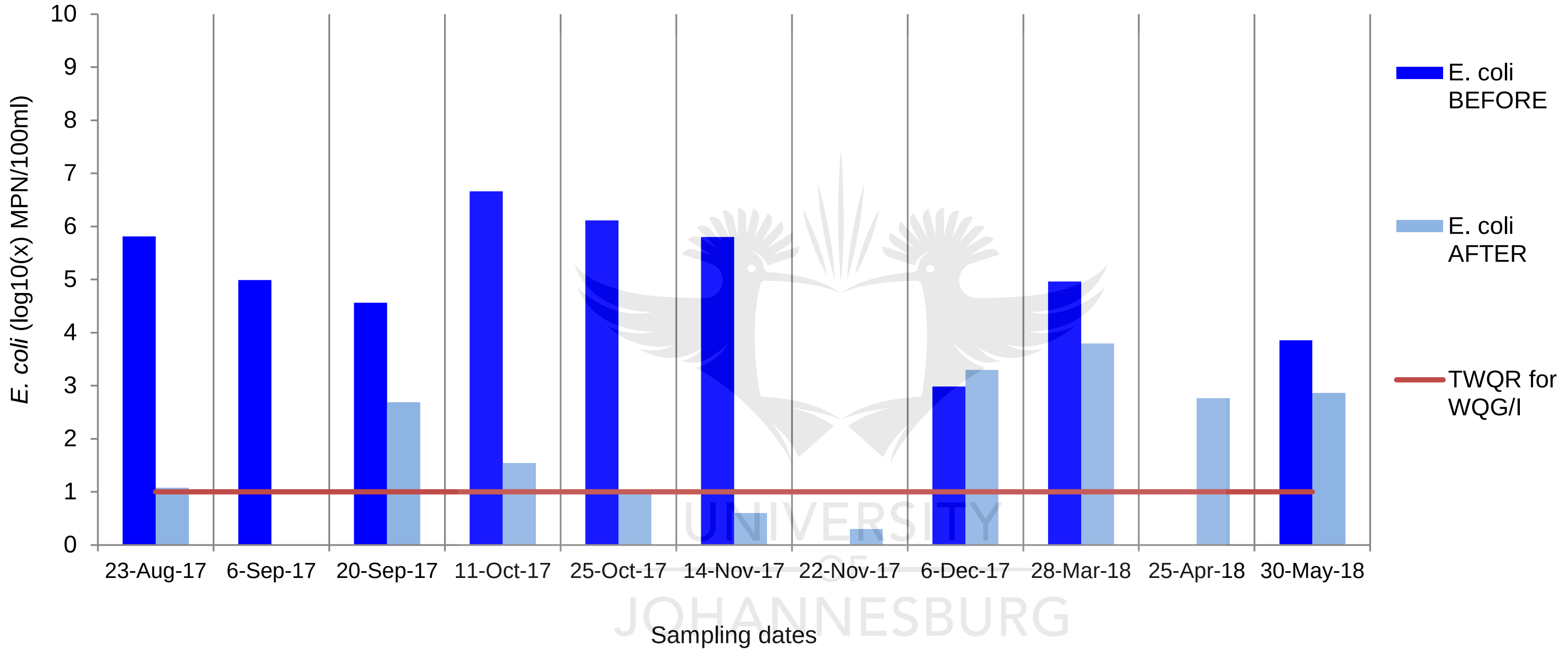


Figure 39. Changes in E. coli (log10(x)) (MPN/100 mL) over time in greywater, before and after treatment by the Z-AW including the TWQR for the WQG/I (DWAF, 1996a) for E. coli.

Table 22. Water quality metal results (mean ± SE) post-treatment for the Z-AW.

Water Quality Parameter	Unit	Mean ± SE
Ca hardness	mg/L $CaCO_3$	118.09 ± 19.23
Mg hardness	mg/L $CaCO_3$	34.35 ± 5.18
B	µg/L	62.27 ± 6.16
Ca	mg/L	47.59 ± 7.75
K	mg/L	3.79 ± 0.37
Mg	mg/L	8.40 ± 1.27
Na	mg/L	14.01 ± 2.37

There were no significant differences for any of the metals, namely B, Ca, K, Mg, Na, Ca hardness or Mg hardness, analysed from the greywater between pre- and post-treatment by the Z-AW (Table 22). There was a small and non-significant increase (means ± SE) in Ca hardness (94.73 ± 20.78; 118.09 ± 19.23 mg/L $CaCO_3$, respectively), and Ca (38.09 ± 8.39; 47.59 ± 7.75 mg/L, respectively).

There was a small and non-significant decrease in Mg hardness (32.36 ± 5.98; 34.35 ± 5.18 mg/L $CaCO_3$, respectively), B (93.91 ± 17.41; 62.27 ± 6.16 µg/L, respectively), K (3.96 ± 0.90; 3.79 ± .37 mg/L, respectively), Mg (7.87 ± 1.46; 8.40 ± 1.27 mg/L, respectively), and Na (22.00 ± 5.68; 14.01 ± 2.37 mg/L, respectively). Sodium (Na) and B concentrations before and after treatment were well below the TWQR for the WQG/I (DWAF, 1996a).

4.5.5. Plant health analysis

Table 23. The correlation coefficient values between average temperature per day (°C) and six plant health criteria, for the Z-AW at Zwartkopjes, Rand Water.

Plant health criteria	Correlation coefficient
Leaf health	0.47
Leaf discolouration	0.39
Plant pests	-
Fungus/diseases	-
Flowers	0.33
Abundance (% of surface area) and height (cm)	0.10

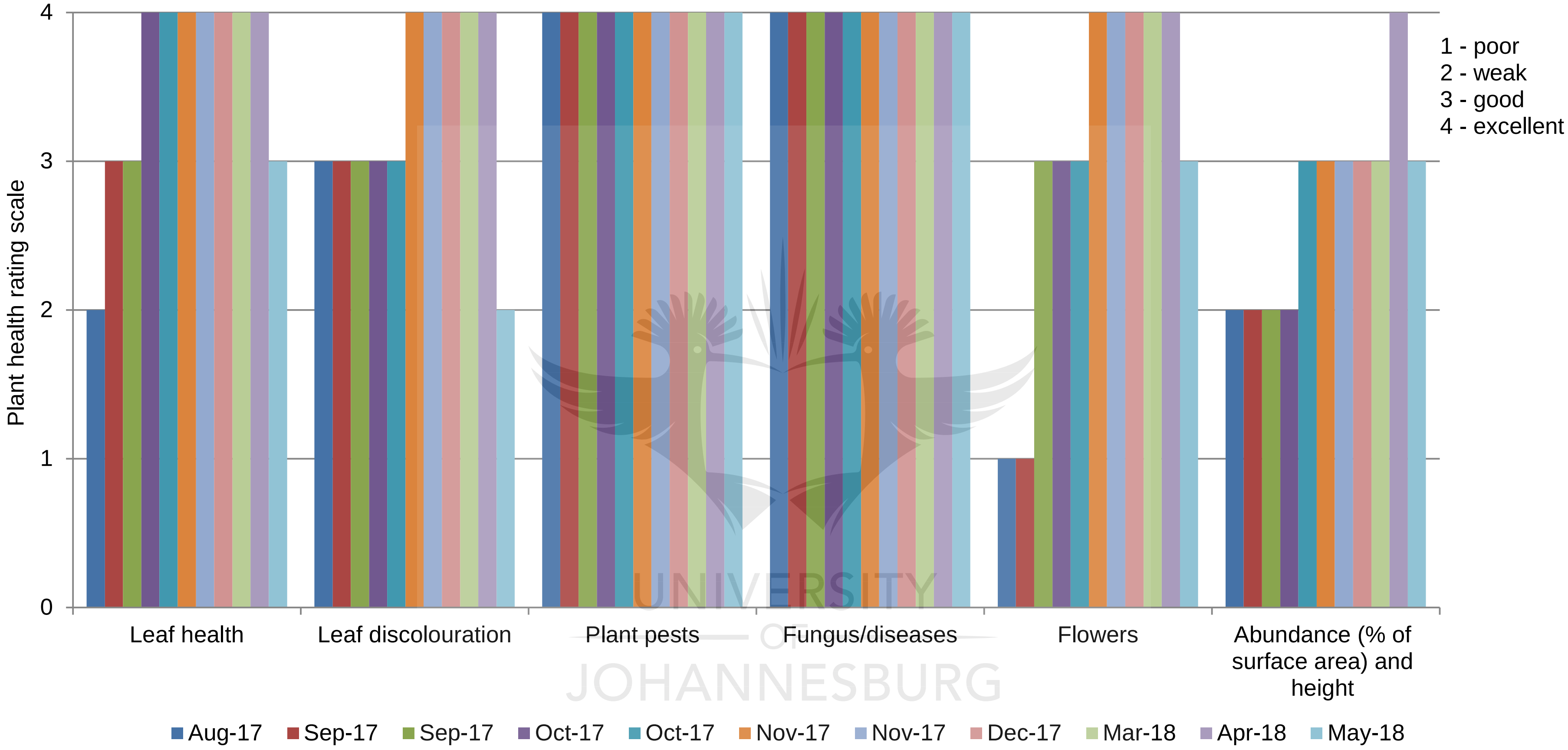


Figure 40. Results of the plant health rating scale to analyse the growth and health patterns of plants growing over the sampling period in the Z-AW, Zwartkopjes, Rand Water.

There was no correlation between average temperatures (°C) per day of sampling and any of the plant health criteria over the sampling period for the Z-AW (Table 23).

The plants growing in the Z-AW had an average health rating of 86.36%, the highest rating of the three wetlands. No plant pests, diseases or fungus infections were noticed on the plants growing in this wetland over the whole sampling period (Figure 40).

4.6. One-way ANOVA comparisons for water quality parameters

Table 24. One-way ANOVA results (P - and F - values) for comparisons of the water quality of pre-treatment domestic greywater (n = 11) between three CW at the Environmental Management Services Department, Zwartkopjes, Rand Water (d.f. = 2, 30). ***Bolded*** *P-values are regarded as significant at the P = 0.05 level.*

Water Quality Parameter	Unit	One-way ANOVA results	
		P	*F*
DO	mg/L O_2	0.84	0.18
Ca hardness	mg/L $CaCO_3$	0.05	3.23
Mg hardness	mg/L $CaCO_3$	0.89	0.12
Cl	mg/L	**0.03**	3.87
NO_3	mg/L as N	**0.003**	6.97
SO_4	mg/L	0.11	2.34
B	µg/L	0.13	2.15
Ca	mg/L	0.06	3.21
K	mg/L	**0.01**	5.18
Mg	mg/L	0.90	0.11
Na	mg/L	0.54	0.62
EC	mS/m	0.20	1.69
Mg alkalinity (M Alk)	mg/L $CaCO_3$	**0.005**	6.27
pH	-	0.57	0.57
Temperature	°C	0.25	1.44
TDS (TDS_CALC)	mg/L	0.48	0.76
TP	mg/L	**<0.05**	11.97
Turbidity	NTU	**<0.05**	13.27
E. coli	MPN/100mL	0.17	1.87
Oil and grease	mg/L	**<0.05**	15.97
TOC	mg/L as C	**<0.05**	31.19

One-way ANOVAs were used to compare the difference in twenty-one water quality parameters of pre-treated greywater, between three CW, namely the MO-AW, N-AW, and Z-

AW (Table 24). Overall, the untreated greywater passed through the MO-AW showed higher pollutant concentrations than the untreated greywater passed through the other two CW, specifically for anions. The Z-AW pre-treatment greywater had higher concentrations of salts, alkalinity, and hardness than the other two CW overall. The N-AW pre-treatment greywater only showed higher concentrations of oil and grease, compared to the other two CW.

There were significant differences between the greywater water quality of the three CW pre-treatment only for Cl, NO_3, K, Mg alkalinity, TP, turbidity, oil and grease, and TOC.

Post-hoc Tukey Studentized Range tests (α, P = 0.05) are shown by different superscript letters indicating the means (± SE) with significant differences (Table 25). Calcium (Ca) hardness concentration and Ca was significantly lower for pre-treatment greywater at the N-AW than at the MO-AW. Chlorine (Cl) concentration was significantly lower for pre-treatment greywater at the Z-AW than at the MO-AW. Concentrations of NO_3 and TP were significantly higher at the MO-AW compared to both the N-AW and Z-AW. The pre-treated greywater at the MO-AW had significantly higher concentrations of K than that at the Z-AW. Magnesium (Mg) alkalinity was significantly higher for the pre-treated Z-AW greywater than for the same at the MO-AW. Turbidity was significantly higher in pre-treated greywater for both the MO-AW and N-AW than for the Z-AW. Pre-treated greywater at the N-AW had a significantly higher concentration of oil and grease than at the Z-AW, as did the pre-treated greywater at the MO-AW. The TOC concentration of pre-treated greywater was significantly higher for the MO-AW than for the N-AW, and the Z-AW, while the TOC concentrations for the N-AW were also significantly higher than the Z-AW.

One-way ANOVAs were also used to compare the water quality of greywater post-treatment between the three research wetlands, namely MO-AW, N-AW, and Z-AW. Overall, water quality post-treatment for the Z-AW was better than that of the other two CW, with a significant lower level of anions, metals, pathogens, and organics (Table 26).

Table 25. Comparisons of the water quality of pre-treatment domestic greywater (mean ± SE) between three CW at the Environmental Management Services Department, Zwartkopjes, Rand Water. Means with different superscript letters are significantly different at the P = 0.05 level.

Water Quality Parameter	Units	MO-AW	N-AW	Z-AW
DO	mg/L O_2	1.77 ± 0.88	1.34 ± 0.84	1.15 ± 0.56
Ca hardness	mg/L $CaCO_3$	70.18 ± 9.91^{A}	45.91 ± 4.86^{B}	94.73 ± 20.78^{A}
Mg hardness	mg/L $CaCO_3$	35.55 ± 4.51	33.91 ± 2.57	32.36 ± 5.98
Cl	mg/L	40.09 ± 9.48^{A}	29.91 ± 3.10$^{A; C}$	14.77 ± 5.14$^{B; D}$
NO_3	mg/L as N	3.84 ± 1.11^{A}	1.49 ± 0.35$^{B;C}$	0.37^{C} ± 0.06$^{B;C}$
SO_4	mg/L	11.63 ± 1.73	11.19 ± 2.31	38.50 ± 17.48
B	µg/L	120.73 ± 19.02	151.00 ± 21.80	93.91 ± 17.41
Ca	mg/L	28.27 ± 4.00^{A}	18.45 ± 1.93^{B}	38.09 ± 8.39^{A}
K	mg/L	11.76 ± 2.92^{A}	5.84 ± 0.56^{A}	3.96 ± 0.90^{B}
Mg	mg/L	8.60 ± 1.10	8.25 ± 0.63	7.87 ± 1.46
Na	mg/L	29.27 ± 4.30	27.91 ± 4.59	22.00 ± 5.68
EC	mS/m	39.82 ± 4.18	30.91 ± 1.70	44.27 ± 7.84
Mg alkalinity (M Alk)	mg/L $CaCO_3$	64.64 ± 7.35^{B}	92.18 ± 9.69^{A}	148.73 ± 27.06^{A}
pH	-	5.29 ± 0.14	6.06 ± 0.15	5.73 ± 0.86
Temperature	°C	22.97 ± 0.81	23.03 ± 1.03	19.08 ± 3.00
TDS (TDS_CALC)	mg/L	239.91 ± 31.88	189.91 ± 18.93	250.82 ± 52.84
TP	mg/L	1.45 ± 0.33^{A}	0.39 ± 0.15$^{B; C}$	0.04 ± 0.01$^{B; C}$
Turbidity	NTU	765.00 ± 114.50^{A}	722.27 ± 114.56$^{A; C}$	140.36 ± 36.02$^{B; D}$
E. coli	MPN/100mL	3 794 592.73 ± 1 528 214.57	17 909 276.36 ± 11 509 916.54	675 027.27 ± 413 156.82
Oil and grease	mg/L	801.82 ± 173.10^{A}	1 108.64 ± 166.45$^{A; C}$	31.96 ± 11.46$^{B; D}$
TOC	MPN/100mL	363.73 ± 47.22^{A}	156.55 ± 24.74$^{B; D}$	21.08 ± 4.74$^{C; E}$

Table 26. One-way ANOVA results (P - and F - values) for comparisons of the water quality of post- treatment domestic greywater (n = 11), between three CW at the Environmental Management Services Department, Zwartkopjes, Rand Water (d.f. = 2, 30). Bolded P - values are regarded as significant at the P = 0.05 level.

Water Quality Parameter	Unit	One-way ANOVA results	
		P	***F***
DO	mg/L O_2	0.29	1.29
Ca hardness	mg/L $CaCO_3$	0.27	1.36
Mg hardness	mg/L $CaCO_3$	0.38	1.01
Cl	mg/L	**<0.05**	10.70
NO_3	mg/L as N	**0.01**	5.19
SO_4	mg/L	**0.001**	8.37
B	µg/L	0.08	2.71
Ca	mg/L	0.27	1.39
K	mg/L	**0.001**	8.88
Mg	mg/L	0.44	0.85
Na	mg/L	**0.010**	5.43
EC	mS/m	0.22	1.58
Mg alkalinity (M Alk)	mg/L $CaCO_3$	0.11	2.35
pH	-	0.16	1.95
Temperature	°C	0.66	0.42
TDS (TDS_CALC)	mg/L	0.22	1.58
TP	mg/L	0.83	0.19
Turbidity	NTU	0.61	0.51
E. coli	MPN/100mL	**0.02**	4.31
Oil and grease	mg/L	**0.001**	8.47
TOC	mg/L as C	**<0.05**	25.73

Significant differences in the greywater water quality after treatment between the three CW were found for Cl, NO_3, SO_4, K, Na, *E. coli,* oil and grease, and TOC (Table 26).

Table 27. Comparisons of the water quality of post-treatment domestic greywater (mean ± SE) between three CW at the Environmental Management Services Department, Zwartkopjes, Rand Water. Means with different superscript letters are significantly different at the P = 0.05 level.

Water Quality Parameter	Units	MO-AW	N-AW	Z-AW
DO	mg/L O_2	1.28 ± 0.82	1.35 ± 0.69	2.82 ± 0.78
Ca hardness	mg/L $CaCO_3$	95.18 ± 16.03	83.73 ± 7.14	118.09 ± 19.23
Mg hardness	mg/L $CaCO_3$	41.82 ± 5.70	44.73 ± 5.10	34.35 ± 5.18
Cl	mg/L	40.36 ± 6.65^{A}	31.00 ± 4.97^{A}	9.45 ± 1.21$^{B; C}$
NO_3	mg/L as N	2.82 ± 0.88^{A}	0.82 ± 0.38$^{B; C}$	0.48 ± 0.03$^{B; C}$
SO_4	mg/L	3.92 ± 0.79^{B}	34.56 ± 13.38^{A}	72.27 ± 15.50^{A}
B	µg/L	85.27 ± 14.08	91.18 ± 4.68	62.27 ± 6.16
Ca	mg/L	38.18 ± 6.42	33.64 ± 2.86	47.59 ± 7.75
K	mg/L	8.68 ± 1.17^{A}	5.86 ± 0.73$^{B; C}$	3.79 ± 0.37$^{B; C}$
Mg	mg/L	10.29 ± 1.34	10.25 ± 0.85	8.40 ± 1.27
Na	mg/L	27.62 ± 4.70$^{A; B}$	28.73 ± 3.07$^{A; B}$	14.01 ± 2.37^{C}
EC	mS/m	54.27 ± 5.91	44.73 ± 3.21	42.50 ± 5.38
Mg alkalinity (M Alk)	mg/L $CaCO_3$	94.18 ± 23.86	148.18 ± 8.67	122.82 ± 16.92
pH	-	6.33 ± 0.64	7.11 ± 0.09	7.33 ± 0.11
Temperature	°C	21.03 ± 2.29	22.79 ± 1.03	22.80 ± 1.03
TDS (TDS_CALC)	mg/L	338.64 ± 36.48	265.82 ± 28.31	266.82 ± 34.21
TP	mg/L	0.06 ± 0.02	0.06 ± 0.01	0.07 ± 0.01
Turbidity	NTU	97.82 ± 17.48	136.73 ± 29.81	74.24 ± 68.60
E. coli	MPN/100mL	61 071.09 ± 25 308.73^{A}	17 016.73 ± 5 824.77^{A}	916.8 2 ± 561.97^{B}
Oil and grease	mg/L	15.42 ± 2.49^{A}	8.42 ± 0.97$^{B; C}$	6.73 ± 0.60$^{B; C}$
TOC	MPN/100mL	95.14 ± 15.90^{A}	23.16 ± 3.03$^{B; C}$	5.65 ± 0.67$^{B; C}$

Post-hoc Tukey Studentized Range tests (α, *P* = 0.05) (Table 27) with different superscript letters show means (± SE) with significant differences for twenty-one water quality parameters. Chlorine (Cl) concentrations were significantly lower for the post-treatment greywater at the Z-AW, than at both the MO-AW and the N-AW. The MO-AW treated greywater had significantly higher NO_3, K, oil and grease, and TOC concentrations than both the N-AW and the Z-AW treated greywater. Sulphate (SO_4) concentrations for the Z-AW were significantly higher post-treatment than for the MO-AW. Sodium (Na) concentrations for both the N-AW and the MO-AW treated greywater was significantly higher than the Z-AW. The treated greywater from the Z-AW had significantly lower *E. coli* counts than both the MO-AW and the N-AW treated greywater.

Chapter 5: Discussion

5.1. Greywater quality pre-treatment

Greywater may contain pollutants that are harmful to human and environmental health, including metals such as B and pathogens (Engelbrecht and Murphy, 2006). Powdered laundry detergents are often the source of pollutants in greywater, specifically salts and P, which can negatively affect soil structure and plant growth, respectively (Morel, 2005). Household chemicals that may be present in greywater, such as laundry detergent and dishwashing liquid, are often the source of pollutants such as PO_4 and Na, while B is found in soaps, detergents, and anti-septic agents. Laundry and kitchen wastewater can introduce microorganisms and pathogens into a greywater stream (Carden *et al*., 2007). The source of greywater will affect its characteristics based on parameters such as household inhabitants, chemicals used, personal care products, medication used, and waste disposal (Roesner *et al*., 2006). Greywater from clothes and dishwashers is usually high in bleach, foam, hot water, NO_3, oil and grease, PO_4, salinity, soaps, Na, SS, and turbidity, and will have a high pH (Roesner *et al*., 2006). Greywater from baths, showers, and kitchen sinks is characteristically high in bacteria, hot water, odour, oil and grease, soaps, SS, turbidity, and in the case of kitchen sinks, organic matter and food particles (Roesner *et al*., 2006).

Generally, there are two aspects of greywater quality that need to be resolved when the use and disposal of greywater is concerned, namely human health aspects (the prevention of risk of infection by pathogens), and soil conditions (the prevention of soil damage as a result of high concentrations of salinity) (Carden *et al*., 2007).

The mean (± SE) values of various water quality parameters of the greywater influent used in this study, did not vary greatly in comparison with influent analysed in other studies (Table 28) (Engelbrecht and Murphy, 2006; Avery *et al.*, 2007; Jokerst *et al*., 2009; Chan, 2013; Laaffat *et al*., 2015; Arden and Ma, 2018). Dissolved oxygen (DO) was slightly higher than that recorded by Jokerst *et al*. (2009). *Escherichia coli* counts for this study were orders of magnitude higher than those recorded for all of the studies compared except for Engelbrecht and Murphy (2006), who used greywater from bathroom and kitchen sinks and shower water. Avery *et al*. (2007), made mention of the wide range in water quality of greywater; dilution of pollutants may occur with high volumes of water passed into the system.

Engelbrecht and Murphy (2006), noted that K concentrations are generally higher in kitchen dishwater than in bathwater. Potassium (K) concentrations were significantly higher in the

MO-AW greywater influent, which consisted of both kitchen sink and bathroom basin wastewater, than the other two systems. However, there was no significant difference in the greywater influent K concentrations between the N-AW and the Z-AW, even though the N-AW also received both kitchen sink and bathroom basin water. It is possible that the influent from the N-AW was diluted since it also received shower water. Additionally, there were fewer people using the N-AW facilities (± 10) as opposed to those using the MO-AW facilities (± 20), especially the kitchen facility.

There was no significant difference in the concentration of B or Na present in greywater pre-treatment between any of the sources. However, total PO_4 concentrations varied significantly across all sources, with concentrations decreasing as follows: MO-AW>N-AW>Z-AW (Table 25). Carden *et al*. (2007), also noted that PO_4 concentrations were exceedingly high in greywater containing dishwashing and laundry waste flows. As expected, concentrations of oil and grease were significantly higher for greywater containing kitchen basin wastewater, namely the MO-AW and N-AW sources, as follows: N-AW=MO-AW>Z-AW (Table 25). Concentrations of oil and grease for the MO-AW and N-AW pre-treated greywater were high enough to be of concern for the potential negative effects on soil and plants, and highlighted the need for fat traps pre-treatment (Table 25) as per Carden *et al*. (2007).

A study conducted by Rodda *et al*. (2010), suggested that kitchen greywater should not be used to irrigate small-scale crops and food gardens, especially if not analysed for pollutants regularly, as a result of the potential for high loads of microorganisms, oil and grease, and SS. In addition, the use of laundry water should be prevented as the high pH and salinity loads may be harmful to humans, soils, and plants (Rodda *et al*., 2010).

Rodda *et al*. (2010), further developed a guidance report on the use of greywater for small-scale agriculture and food garden irrigation, with a set of greywater quality guidance ranges for a selection of constituents or parameters. These guidelines were set to assist in reducing the human and environmental health risks of using greywater and presented the values recommended for minimal risk to human, plant, and soil health (Table 29).

Table 28. Comparison of the concentrations of selected water quality parameters of greywater pre-treatment by CW for this study with greywater water quality parameters from other studies (Engelbrecht and Murphy, 2006; Avery et al., 2007; Carden et al., 2007; Jokerst et al., 2009; Chan, 2013; Laaffat et al., 2015; Arden and Ma, 2018).

	This study (mean ± SE)	**Engelbrecht & Murphy (2006)**	**Avery *et al.* (2007)**	**Carden *et al*. (2007)**	**Jokerst *et al.* (2009)**	**Chan (2013)**	**Laaffat *et al.* (2015)**	**Arden and Ma (2018)**
B (µg/L)	0.12 ± 0.007	0.1 - 9.5	-		-	-	-	-
Cl (mg/L)	29.81 ± 6.4	17 - 144	-		-	-	-	-
DO (mg/L)	1.66 ± 0.13	-	-		0.11	-	-	-
E. coli	$1.6 \times 10^6 \pm 1.1 \times 10^6$ (MPN/100mL)	$0\text{-}1.0 \times 10^8$ (MPN/100mL)	3.1 ± 0.2 ($\log_{10}(y+1)$ CFU/100cm^3)		-	20 300 ± 7.7 (CFU/100mL)	$5 \times 10^3 \pm 2.1$ (CFU/100mL)	3.6 - 6.7 (CFU/100mL)
N (mg/L)	1.74 ± 1.06	0.1 - 0.35	1.5 ± 0.2		-	-	7.1 ± 2.1	1.1 - 74
pH	6.16 ± 0.49	5.5 - 9.5	7.1 ± 0.0	3.3 - 10.9	6.3	7.73 ± 0.2	7.92 ± 0.02	-
Na (mg/L)	28.91 ± 1.08	25 - 665	-	96 - 1700	-	-	-	-
TDS (mS/m)	252.15 ± 28.54	212 - 2990	-		-	-	-	
Temperature (°C)	23.72 ± 0.58	-	-		-	-	24.6 ± 0.15	-
Turbidity (NTU)	494.80 ± 173.35	-	27.9 ± 9.2		27.4	103 ± 35	-	19 - 444
TP (mg/L)	0.58 ± 0.44	0.87 - 131	0.7 ± 0.1	0.7 - 769	-	-	0.8 ± 0.5	0.06 - 500

Table 29. Guidelines for seven water quality parameters for the acceptable use of greywater on small-scale crops and food gardens to prevent human, plant, and soil health risks (adapted from Rodda et al., 2010).

Water quality constituent	Water quality suitable for unrestricted use with minimal risk to human, plant, and soil health	Water quality not suitable for use in irrigation as it places extreme risk on human, soil, and plant health
Oil and grease (mg/L)	< 2.5	> 20
pH	6.5 - 8.4	< 6 > 9
B (µg/L)	< 0.5	> 6.0
SAR	< 2.0	> 15.0
Total P (mg/L)	< 10	> 50
Total inorganic N (mg/L)	< 10	> 60
***E. coli* (CFU/100mL)**	< 1	> 10^7

5.2. Macrophytes and constructed wetlands (CW) efficiency

It has been shown that the presence of macrophytes in CW can substantially increase nutrient removal from wastewater in comparison with unplanted CW (Fraser *et al.*, 2004; Zhou *et al*., 2017). Brix and Shierup (1989), described the efficiency with which aquatic plants assimilate nutrients and other pollutants, and the potential for the use of macrophytes in wastewater treatment systems. The presence of above-ground macrophytes has been linked to an increase in the strong redox reactions that occur within SSF CW and facilitate the efficient removal of contaminants (Caselles-Osorio and García, 2007). Vegetated CW have been shown to be more efficient in removal of organics, N, and P; however, less so in the removal of SO_4 and NO_3, which require anoxic conditions (Vymazal, 2011). Macrophytes utilised in horizontal SSF wetlands should have a variety of characteristics that will increase their efficiency at pollutant removal. These include tolerance to high organic and nutrient loading, the presence of rhizomes and roots to which bacteria can attach, and large above-ground biomass for insulation from cold temperatures and nutrient removal through biomass harvesting (Vymazal, 2011; Wu *et al*., 2015). Emergent macrophytes in horizontal SSF systems provide oxygen to promote the removal of BOD, and to facilitate nitrification (Brix and Schierup, 1989). Wu *et al.* (2015), noted that emergent plants such as *Scirpus* spp., *Juncus* spp., and *Eleocharis* spp., amongst others are the most common species used in CW. Two of the most common aquatic plant species were used in the CW for this research project, namely *J. oxycarpa*, and *E. dregeana* (Finger Sedge), planted in the MO-AW and the N-AW.

All three CW were planted with emergent macrophytes, specifically *C. prolifer* (Miniature Papyrus), *C. denudatus*, *S. brachyceras* (Water Reed), *J. oxycarpa*, *E. dregeana* (Finger Sedge), *F. complanata*, *B. erecta* (Water Parsnip), *C. bulbispermum* (Orange River Lily), *K. ensifolia* (Torch Lily), and *Z. aethiopica* (Arum Lily) (Figure 11-13). Emergent macrophytes grow vegetative biomass above the surface of the water with roots submerged below (Hoffman *et al.,* 2011). The surface biomass generally covers more than 50% of the surface of the wetland (Vasudevan *et al.,* 2011). Emergent macrophytes tend to have an overall low nutrient removal efficiency of 5%; however, metal removal efficiency is mostly better and is often more than 30% (Srivastava *et al.,* 2008).

Fraser *et al.* (2004), showed that systems grown in monoculture are less efficient at wastewater treatment compared to more species-diverse systems, although the differences were not significant. This was also demonstrated by Zhou *et al.* (2017), in a study on the effect of vegetation and microbiological activity on nutrient removal in horizontal SSF CW. Systems planted with more than one species of macrophytes will show a more consistent treatment of wastewater due to the resistance to seasonal variations (Karathanasis *et al.,* 2003). Following the plant health rating scale (Stelli and Mphomane, 2016) used to determine overall plant health for this study, the Z-AW showed the highest score at 86.36% (Figure 40), only slightly better than the MO-AW (82.95%) (Figure 22) and N-AW scores (81.06%) (Figure 35). The Z-AW is also a monoculture system, planted with *S. brachyceras* (Water Reed) only. This system had significantly lower concentrations of pollutants than the other two systems post-treatment. However, it was not as effective at removing pollutants from greywater compared to the other systems, with significant decreases in TOC (P = 0.007) (Figure 37) and DO (P = 0.001) (Table 20) only. It must be noted that the pre-treatment water quality of the Z-AW was better than the other two systems in all pollutants except for salts. While there was no significant difference between the systems for *E. coli* counts pre-treatment, the Z-AW had significantly lower post-treatment *E. coli* counts (P = 0.02). This reason for this may be that *S. brachyceras*, which was planted in the Z-AW, and is described as a robust perennial (Browning, 1991), established more rapidly than the range of macrophytes planted in the MO-AW and N-AW. It is also possible that the variety of different macrophytes planted in the MO-AW and N-AW provided more competition amongst the species, reducing their effectiveness at removing pathogens.

The MO-AW and N-AW were planted with between 8 - 10 different aquatic plant species. The MO-AW system removed a significant amount of oil and grease (P = 0.001), TOC (P < 0.05), *E. coli* (P = 0.04), turbidity (P < 0.05), SO_4 (P = 0.002), and TP (P = 0.002) from the treated water. Pre-treatment concentrations of anions for the MO-AW were significantly higher than the other systems, and concentrations of organics, NO_3, and K were significantly higher post-treatment than the other systems (Table 27), as discussed further in this chapter.

The N-AW system showed a significant decrease, post-treatment, in oil and grease ($P < 0.05$), TOC ($P < 0.05$), turbidity ($P = 0.001$), TP ($P = 0.05$), and B ($P = 0.03$). The pre-treatment greywater for the N-AW was significantly higher in organics than the other two systems; however, post-treatment water quality was not significantly higher for this system compared to the other two systems (Table 27).

Vymazal's (2011), review of pollutant removal by macrophytes in HSSF wetlands indicates that certain aquatic plants are more efficient at removing pollutants than others. He suggested that systems planted with macrophytes are more proficient at treating wastewater than those that are unplanted (Vymazal, 2011). Wu *et al.* (2015), also suggested that assimilated pollutants may be re-introduced into CW when macrophytes die and decay, reducing the treatment efficiency of the system, and recommended that appropriate harvesting strategies be implemented to prevent this. Conversely, Vymazal (2007), noted that the decomposition of plant biomass and the subsequent release of C and N back into wetland water is crucial to the wetland N-cycle and promotes nitrification and other processes. While the presence of emergent macrophytes may not have a significant effect on the treatment efficiency of CW, it appears that aquatic plants mostly have a positive effect, specifically on the removal of N and phosphorus from wastewater (Vymazal, 2011).

While it is difficult to conclusively determine the effect of monoculture versus polyculture CW systems on the removal of pollutants from greywater, it can be said that the MO-AW and N-AW systems effectively removed TP from wastewater, corroborating Vymazal's (2011) statement on PO_4 removal.

5.3. The role of biofilms in pollutant removal

The presence of biofilms in CW is supported by gravel and stone media that act as habitats for these microorganisms (Vasudevan *et al.,* 2011). Biofilms can also be found on plant roots (Wong *et al.,* 1999), specifically in aerobic areas where nitrification or N assimilation can occur (Wastewater Gardens, 2013). These microbial communities are also able to remove pathogens from wastewater through adsorption, and biologically assimilate organic and inorganic nutrients to reduce concentrations (Mthembu *et al*., 2013). Generally, microbial communities as biofilms are responsible for the removal of soluble organic matter in SSF wetlands (Hoffman *et al*., 2011). In a study on the growth and functionality of microbial communities in CW, Lv *et al*. (2017), showed that biofilm activity was higher in saturated systems, such as SSF wetlands compared to unsaturated systems. The presence of macrophytes in CW also encouraged biofilm activity and resulted in the removal of pollutants such as total N, NH_4, total P, and TOC (Lv *et al*., 2017).

The MO-AW and N-AW systems analysed in this study, showed a significant decrease post-treatment in anions, namely TP (Table 13 and Table 17, respectively) (P = 0.002 and P = 0.05, respectively) and TOC (P < 0.05 for both systems) (Figure 20 and Figure 30, respectively). The Z-AW system showed a significant decrease in TOC post-treatment (P = 0.007) only (Figure 37).

The removal of organic compounds from wastewater typically occurs through a variety of sub-surface processes including filtration, sorption, oxidation/reduction, and biodegradation. Biodegradation and sorption occurs through the activity of microbial communities found growing in biofilms on plant roots and substrate (Jasper *et al.,* 2013). Constructed wetlands (CW) generally show a high removal of organics primarily through microbial activity (Vymazal, 2010). The presence of macrophytes can also encourage the growth of microbial communities in systems, as plant roots provide increased surface area for biofilm attachment (Chan, 2013).

The systems analysed for this research showed significant decreases in organics pre- and post-treatment. The saturated conditions of these wetlands and the presence of macrophytes may have potentially increased the chance of growth of microbial communities and the formation of biofilms, which may have facilitated the effective removal of organics from greywater.

5.4. Removal of nutrients and organics

The WQG/I (DWAF, 1996a) outlines the physical, chemical, and biological water parameters and ranges that are required for water to be used safely in irrigation, primarily for crop production, regardless of its source. The document provides a TWQR for each water quality parameter, which ensures that the level or concentration of that constituent in water would have no negative effects on its suitability for the intended use (DWAF, 1996). The quality of greywater post-treatment was analysed in this project and compared to the TWQR for water use for irrigation, according to the DWAF (1996a) standards, as well as to recommendations from other studies (Table 30) (Avery *et al*., 2007; Jokerst *et al*., 2009; Chan, 2013; Laaffaat *et al*., 2015; Arden and Ma, 2018). Table 30 shows that Cl and NO_3 concentrations of post-treatment greywater for this study were below the TWQR for the WQG/I (DWAF, 1996a).

Nitrate (NO_3) concentrations post-treatment in this study were similar and lower than those recorded in other similar studies (Avery *et al*., 2007; Laaffaat *et al*., 2015) (Table 30).

5.4.1. Nitrogen (N) and organics removal

The removal of N from wastewater is essential in any treatment process, as N as a pollutant can cause eutrophication, toxicity in aquatic organisms, and a reduction in DO in receiving water. High concentrations of N, such as that generally found in dishwater, can also negatively impact groundwater quality (Murphy, 1996). Nitrate (NO_3) is present in wastewater as an inorganic form of N and is removed through the biological process of denitrification. This process can however be limited by the availability of organic C (Saeed and Sun, 2012). Total inorganic N, also known simply as N, is often used as a parameter with which to measure water quality, and refers to all inorganic N present in water, namely NH_3, NH_4, NO_3, and NO_2. Other organic parameters such as TOC and total P are closely related to the presence of organic N (DWAF, 1996a).

Total organic carbon (TOC) is used as a measurement for organics in greywater as it depicts the risk of oxygen depletion in the water as a result of the decomposition of organic matter, the formation of biofilms, and impacts on plants and soils (Rodda *et al*., 2010). Ramprasad and Philip (2016), noted that experimental horizontal SSF wetlands decreased TOC concentrations to 1.82 mg/L after treatment. In this study, although there was a significant decrease in TOC post-treatment across all three systems, concentrations of TOC were high post-treatment, with an average value of 42.11 ± 27.13 mg/L (Table 30). The US EPA guidelines for water re-use (2012), suggested that the acceptable concentration of TOC in reclaimed water is between 4 and 8 mg/L.

There was a significant decrease in organics (oil and grease) (Figure 19) and TOC (Figure 20) after treatment by the MO-AW but no significant changes in the concentration of NO_3 post-treatment (Table 13). The same was found for the N-AW (oil and grease) (Figure 29) and TOC (Figure 30), and the Z-AW (TOC only) (Figure 37). Between 83 and 99% of oil and grease was removed from treated greywater, and between 74 and 81% of TOC was removed (Table 30). Nitrate (NO_3) removal rates were much lower, with between 6 and 53% NO_3 removed from greywater with treatment by CW (Table 30). Nitrate (NO_3) concentrations in greywater post-treatment for all CW analysed, were all well below the recommended value

Table 30. Comparison of the concentrations of selected water quality parameters of greywater post-treatment by CW for this study, with DWAF's (1996) TWQR for irrigation and water quality guidelines for irrigation (Rodda et al., .2010), as well as results of treatment of greywater with similar CW from other studies (Avery et al., 2007; Jokerst et al., 2009; Chan, 2013; Laaffat et al., 2015; Arden and Ma, 2018).

	This study (means ± SE)	**TWQR (DWAF, 1996)**	**Avery *et al.* (2007) (HF[b])**	**Jokerst *et al.* (2009) (SF[c])**	**Rodda *et al.* (2010)**	**Chan (2013) (HSSF[a])**	**Laaffat *et al.* (2015) (HSSF[a])**	**Arden and Ma (2018) (HSSF[a])**
B (µg/L)	0.08 ± 0.008	0.5	-	-	< 0.5	-	-	-
Cl (mg/L)	27.60 ± 9.32	100	-	-	-	-	-	-
DO (mg/L)	1.92 ± 0.46	-	-	2.18	-	-	-	-
E. coli	23 240 ± 19 017 (MPN/100 mL)	1 (counts/100 mL)	1.25 ± 0.0 ($\log_{10}(y+1)$ CFU/100 cm^3)	-	< 1 (colony-forming units, CFU/100 mL)	344 ± 12 (CFU/100 mL)	$5 \times 10^1 \pm 5$ (CFU/100 mL)	398 (CFU/100 mL)
N (mg/L)	1.25 ± 0.79	5	1.0 ± 0.1	-	-	-	3.89 ± 1.5	-
pH	6.96 ± 0.32	6.5 - 8.4	7.1 ± 0.0	6.5	6.5 - 8.4	7.35 ± 0.24	7.32 ± 0.01	-
Na (mg/L)	24.17 ± 5.17	70	-	-	-	-	-	-
TDS/EC	303.28 ± 20.74 (mg/L)	40 (mS/m)	-	-	-	-	-	-
Temperature (°C)	22.66 ± 0.91	-	-	-	-	-	25.6 ± 0.09	-
Turbidity (NTU)	97.98 ± 13.75	-	10.3 ± 1.0	7.9	-	7.55 ± 5.39	-	38
TP (mg/L)	0.06 ± 0.002	-	0.3 ± 0.1	-	< 10	-	0.47 ± 0.3	2.3

[a]HSSF = horizontal sub-surface flow wetland; [b]HF = horizontal flow; [c]SF = sub-surface flow

for unrestricted use of greywater with minimal risk (as per Rodda *et al*., 2010) (Table 29). However, concentrations of oil and grease were slightly higher than recommended by Rodda *et al*. (2010), with MO-AW post-treatment concentrations (Table 30) only suitable for short-term use with significant risk to human health, and plant and soil conditions. Both the N-AW and Z-AW oil and grease concentrations (Table 30) were below 10 mg/L but above 2.5 mg/L, rendering the post-treatment greywater from these two systems suitable for irrigation of well-drained, chemically stable soils. If greywater high in oil and grease is used over a long period of time, the accumulation of oil and grease may cause water repellency in soils and run-off, ponding, and the downward flow of water (Rodda *et al.,* 2010).

Sub-surface flow (SSF) wetlands have been found to remove organics more efficiently than SF wetlands but are less efficient at removing N, possibly because they do not offer both anaerobic and aerobic conditions simultaneously (Vymazal, 2007). Generally, the removal of total N from wastewater is low in HSSF systems due to their water-saturated nature. Vymazal (2011), suggested combining HSSF systems with vertical flow systems in order to introduce simultaneous aerobic and anaerobic conditions to improve denitrification.

It is possible that the efficient removal of organics in SSF CW is a result of SO_4 reduction by heterotrophic bacteria, especially in the anaerobic conditions found in most CW (Saeed and Sun, 2012). Vymazal (2007), further suggested that SSF wetlands have lower rates of N removal because the magnitude of these processes is low in the free water zone. To facilitate the effective removal of organics and N from wastewater, CW should use substrate that provides an internal carbon source in addition to that occurring in greywater. This will enhance denitrification and organics removal, something which the commonly used gravel media does not do as effectively (Saeed and Sun, 2012). However, the occurrence of clogging of SSHFW media is high, and the hydraulics of the system need to be carefully calculated to ensure optimal oxygen supply for pollutant removal (Saeed and Sun, 2012).

Horizontal SSF wetlands are advantageous in that they facilitate denitrification (reduction of NO_3 in greywater), and the removal of N and P (Saeed and Sun, 2012). Denitrification is described as the conversion of NO_3 to gaseous N by denitrifying bacteria, and results in the removal of N from ecosystems (Bertino, 2010).

The denitrification process during greywater treatment results in the production of alkalinity and $CaCO_3$ (Saeed and Sun, 2012). In the N-AW, a significant increase in Mg alkalinity (mg/L as $CaCO_3$) was observed (Figure 24). For efficient denitrification, the DO concentrations should be kept as low as possible, preferably less than 0.3 to 0.5 mg/L (Bertrino, 2010). Dissolved oxygen (DO) concentrations in pre-treated greywater were 1.34

mg/L for the N-AW (Table 16), 1.77 mg/L for the MO-AW (Table 12) and 1.15 mg/L for the Z-AW (Table 20), which may account for the reduced concentrations of NO_3 pre- and post-treatment.

In a study on efficient SSF CW designs, García *et al.* (2005), showed that more than 50% of TOC present in greywater was removed at the inlet to the CW system, indicating the importance of physical treatment processes such sedimentation and filtration to the treatment of greywater, as well as biochemical processes that occur along the length of the system.

5.4.2. Phosphate (PO_4) removal

Between 23 and 96% of TP was removed from greywater through CW treatment. There was a significant reduction in TP post-treatment for the MO-AW (Figure 17) and the N-AW (Figure 28); pre- and post-treatment concentrations fell well below the recommended range for water quality suitable for unrestricted use, as defined by Rodda *et al*. (2010) (Table 29). The mean (± SE) concentration of TP post-treatment for this study was noticeably lower compared to similar studies (Avery *et al*., 2007; Laaffaat *et al*., 2015; Arden and Ma, 2018) (Table 30). The low concentrations of TP in greywater pre- and post-treatment may be a result of the lack of laundry wastewater in the effluent. Phosphates (PO_4) are generally present in greywater as a result of the use of laundry detergents (Rodda *et al*., 2010). However, recently there has been the release of zero-phosphate detergents in SA (Quayle *et al*., 2010), which should lead to a reduction of PO_4 in greywater in the future. The removal of P from contaminated water passed through a CW system, occurs with the uptake of the nutrient by plants as well as sediment deposition of its insoluble form, provided it is adsorbed to soil particles (Katsenovich *et al*., 2009). The CW systems utilised in this study were not constructed with soil; rather, gravel was used as the sediment. It is possible that the lack of soil particles in the systems reduced their ability to remove P from the greywater.

Phosphorus (P) can be removed from wastewater either though soil adsorption or precipitation. Soil adsorption of P occurs with the movement and accumulation of P to and on the surface of soil minerals. Phosphorous (P) precipitation is the reaction of P with metals such as iron (Fe), Al, Ca, or Mg but this can also occur with other minerals such as $CaCO_3$ (Vymazal, 2007).

The removal of PO_4 from wastewater by CW can occur through microbial uptake but the amount stored is very low. Plant roots are however, responsible for most of the P removal (Vymazal, 2007). Sub-surface flow (SSF) CW, specifically horizontal flow systems, show the most potential for P removal through adsorption and precipitation by substrate media, mainly because the substrate is constantly flooded; however, the use of gravel can reduce this effect as it has a low capacity for sorption (Vymazal, 2007).

5.5. Pathogen removal

Escherichia coli is generally chosen as a microbiological parameter for measurement of pathogens in greywater because it is specific to faecal pollution and is less likely to re-grow in greywater (Rodda *et al*., 2010). The infective dose of *E. coli* as a waterborne pathogen is $1 \times 10^8 – 1 \times 10^{10}$ counts per 100 mL. This is the number of *E. coli* microorganisms that need to be ingested to cause disease (Rodda *et al*., 2010).

Escherichia coli numbers were reduced after treatment by between 98 and 99% across the three CW studies, although a significant difference was found for the MO-AW only. Comparisons of *E. coli* counts in greywater post-treatment by CW, showed that the CW used in this study were slightly less efficient in pathogen removal than similar systems used in other studies (Avery *et al*., 2007; Chan, 2013; Laaffaat *et al*., 2015; Arden and Ma, 2018) (Table 30). Nonetheless, a study by Lakay (2012) on the treatment of greywater with CW, showed similar reductions in *E. coli* counts compared to this study. In addition, the US EPA (2000) has recorded a decrease of coliforms in greywater influent from 2.7×10^5 MPN/100 mL to 5.7×10^4 MPN/100 mL in treated effluent, similar to that seen in this study: MO-AW ($6.1 \times 10^4 \pm 2.5 \times 10^4$ MPN/100 mL) (Table 30); N-AW ($1.7 \times 10^4 \pm 5.8 \times 10^3$ MPN/100 mL) (Table 23); and Z-AW ($9.1 \times 10^2 \pm 5.6 \times 10^2$ MPN/100 mL) (Table 30).

Rodda *et al*. (2011) also noted that acceptable counts of *E. coli* in greywater fall between 1 and 1 000 CFU/100 mL, where greywater can be used with only basic hygiene precautions, but also recognised that it is unlikely that most greywater pathogen counts will fall within this range. It must be noted that *E. coli* counts were measured as MPN per 100 mL in this study, while other studies recorded *E. coli* counts as colony-forming units (CFU) per 100 mL. It has been shown that MPN estimates of *E. coli* concentrations can be one order of magnitude greater than CFU estimates (Cho *et al*., 2010). Recommended counts of *E. coli* in greywater suitable for unrestricted use is < 1 CFU/100 mL, while values above 10^7 are considered extremely risky to human, plant, and soil health and the greywater is not suitable for use in irrigation (Rodda *et al*., 2010). The level of *E. coli* counts in treated greywater for use in restricted irrigation is < 10^5/100 mL (Rodda *et al.,* 2010).

Escherichia coli counts in greywater post-treatment for this study were between 917 and 61 100 MPN/100 mL (Table 30). According to Rodda *et al.* (2010), these counts are considered to be high enough for significant risk to human health, unless irrigation is sub-surface, which then extends the suitable range to 10^7 CFU/100 mL. However, the greywater can be used for irrigation if exposure to crops is limited (Rodda *et al*., 2010). Maimon *et al*. (2014), also suggested that the availability of organic matter and other nutrients in greywater may stimulate the growth of *E. coli,* even in influent that would not normally show high concentrations of the pathogen.

Generally, faecal coliform counts are higher in kitchen greywater compared to laundry or bathroom greywater (Murphy, 1996). Indeed, *E. coli* counts pre-treatment where higher for both the MO-AW and the N-AW than for the Z-AW (Table 25), while counts were significantly higher for the MO-AW and the N-AW compared with the Z-AW for post-treatment effluent (Table 27).

Mthembu *et al*. (2013), reported that studies on pathogen removal by CW showed decreases in *E. coli* counts of between 52% and 99%. Generally, pathogen removal by CW is thought to occur primarily through sedimentation; however, if this reservoir or accumulation of pathogens is disturbed, these pathogens can be released back into the system (Mthembu *et al*., 2013). Avery *et al*. (2007), suggested that the size and surface characteristics of pathogens may influence their ability to adhere to media or substrate surfaces, which will affect the removal of microorganisms from greywater. Microorganisms can be effectively filtered from greywater with soil; however, course soil such as gravel and sand is ineffective as bacteria cannot be 'strained' from the water (Pescod, 1992). The number of microorganisms, including pathogens in greywater, increases with storage time, which means that greywater should be treated immediately and before it reaches an anaerobic state (Carden *et al*., 2007). The presence of thermotolerant or faecal coliforms can indicate the presence of other harmful microorganisms and the potential for the spread of infectious diseases (Rodda *et al*., 2010).

Lakay (2012), noted that a high percentage of *E. coli* removal through treatment does not necessarily correlate to low bacteria numbers in the effluent, as the actual count number is more important than the removal percentage. Nonetheless, none of the treated effluent met the TWQR as prescribed by the WQG/I (DWAF, 1996a) i.e. a coliform count of > 20 CFU/100 mL indicates a significant and increasing risk of infectious disease.

Although the MO-AW showed a significant decrease in *E. coli* counts post-treatment, counts of the pathogen were slightly higher for all the CW post-treatment than is recommended in the literature (Rodda *et al*., 2010). It is possible that pathogens were not removed from the greywater to the recommended standard since the size of the substrate was too large to provide an effective filter. The treated greywater effluent should therefore be used in drip-irrigation only to limit the potential negative effects of pathogenic microorganisms present in the effluent. Lakay (2012), suggested that a short hydraulic retention time (HRT) of between 2 to 4 days may prevent a significant removal of pathogens in greywater, through processes such as natural die-off, predation, sedimentation, filtration, and adsorption. Qomariyah *et al*. (2016), further suggested an optimal HRT of approximately 8 days to ensure effective removal of faecal coliforms of 99.99%. Poor *E. coli* removal may also be a result of cold temperatures during the winter season (Lakay, 2012). An overloading of the system may also result in a reduced efficiency in faecal coliform removal, as a result of decreased adsorption to the biofilm (Wu *et al*., 2016).

5.6. Removal of metals and ions

The removal of metals from greywater by treatment with CW was not significant for any of the systems except for the N-AW, which showed a significant decrease in B before and after treatment (Figure 34). In general, there was a reduction in metals by between 2 and 48% after treatment of greywater. There was a significant increase in Ca hardness and Ca after treatment for the N-AW (Figures 32 and 33). The concentration of B (μg/L as B) and Na (mg/L) in the greywater post-treatment fell within the recommended TWQR of the WQG/I (DWAF, 1996a). The B concentrations measured in this study also fell within those recommended by Rodda *et al.* (2010) (Table 29) for unrestricted use of greywater for irrigation, and were similar to those measured in other comparable studies (Table 30). Murphy (2006), listed the recommended acceptable concentrations for greywater parameters as follows:

- Na: < 70 mg/L;
- K: < 10 mg/L;
- Cl: < 100 mg/L;
- SO_4: < 150 mg/L;
- Mg: 0 - 300 mg/L;
- B: 0.5 μg/L; and
- SAR: < 5.

The mean (± SE) concentrations of Na (24.17 ± 5.17), K (6.46 ± 1.43), Mg (9.74 ± 0.68), Cl (27.6 ± 9.32), SO_4 (40.38 ± 19.86), B (0.08 ± 0.008), and SAR (0.5 – 1.41) for post-treatment greywater analysed for this study (Table 30), were all lower compared to those suggested by Murphy (2006).

Potassium (K) concentrations are generally higher in dishwater than in bathroom basin and shower water (Engelbrecht and Murphy, 1996). This trend was also observed for this study, with higher concentrations of K found in both pre- and post-treatment greywater for the MO-AW and N-AW, as compared with the Z-AW (Table 25 and Table 27).

There was a significant decrease in SO_4 concentration after treatment for the MO-AW (Table 13), but no significant change in SO_4 before and after treatment for the N-AW (Table 17) and Z-AW (Table 21). Overall, 66% of SO_4 was removed from greywater through CW treatment for the MO-AW (Figure 18). However, there was a 69% (non-significant) increase in SO_4 post-treatment for the N-AW and a 35% (non-significant) increase in SO_4 post-treatment for the Z-AW. While SO_4 removal by the N-AW and Z-AW was not effective, concentrations were low enough as per the TWQR as prescribed by the WQG/I (DWA, 1996a) pre- and post-treatment not to cause concern when irrigating with treated greywater.

There was a 48% non-significant decrease in Cl concentration post-treatment for the Z-AW (Table 21), a 5% non-significant increase post-treatment for the N-AW (Table 17), and no change in Cl concentration pre- and post-treatment for the MO-AW (Table 13). Once again, Cl removal by these CW was not effective; however, concentrations of the ion post-treatment were already lower than that prescribed by Murphy (2006) (< 140 mg/L) as acceptable. Indeed, post-treatment Cl concentrations fall well below the prescribed TWQR of < 100 mg/L for the WQG/I (DWAF, 1996a), which prevents the accumulation of Cl at toxic concentrations.

As per DWAF (1996b) the concentration of salts such as $CaCO_3$ in water determines the potential for scaling and corrosion of pipes and other fittings. This is known as total hardness. Scaling refers to an over-saturation of water with salts and can cause the formation of white scale-like growths in pipes, on geyser and kettle elements, and in irrigation equipment. Corrosion, however, is a result of under-saturation of water with salts, whereby the pH of the water is generally more acidic and unprotected structures are 'attacked' and corroded. The Langelier Saturation Index (LSI) indicates the likelihood of water to act as a corrosive agent or to form scale. It is calculated as:

LSI = [(pH) + (temperature factor) + (Ca hardness factor)] + [(total alkalinity factor) - (TDS factor)]; where each parameters factor is calculated according to the Langelier numerical equivalents table (Hach, *n.d.*).

Results of the LSI calculation indicate that the likelihood of corrosive action by post-treatment greywater for the MO-AW (-2.37) and the N-AW (-0.49) is high, as values are

<-0.2. According to the Langelier index range (-0.2 to +0.2) (DWAF, 1996), values below -0.2 indicate an increase in corrosion of metal and concrete. Values between -0.2 and 0.2 indicate no problems with corrosion or scaling. The LSI result for the Z-AW was -0.27, suggesting little to no potential for the treated greywater to act corrosively.

The Aggressiveness Index (AI) is one of the more widely-used methods to determine the corrosiveness of water (DWAF, 1996b):

AI = pH + $\log_{10}$(AH); where A = total alkalinity in mg/L $CaCO_3$; and H = Ca hardness as mg/L $CaCO_3$.

The mean AI of greywater post-treatment by CW in this study was 10.28 for the MO-AW, 11.32 for the N-AW, and 11.49 for the Z-AW. Values between 10 and 11.9 are regarded as moderately aggressive and can cause pipe and equipment corrosion.

Overall, the removal of salts by the CW, specifically affecting the hardness of treated greywater was not effective, as there was no significant change in Ca hardness, Ca, Mg hardness, or alkalinity (Table 14) post-treatment for the MO-AW and Z-AW (Table 22). However, there was a significant increase in Ca (Figure 33), alkalinity, (Figure 24) and hardness (Figure 32) of greywater post-treatment for the N-AW. There was also a significant increase in turbidity post-treatment for the N-AW (Figure 27). Nonetheless, concentrations of Ca for all three CW fell within the TWQR (32-80 mg/L) (DWAF, 1996b) for no health effects, as per the Water Quality Guidelines for Domestic Use (WQG/DU). A similar pattern was observed with Mg concentrations that were less than the TWQR of 30 mg/L for the WQG/DU, which is the range at which the metal will have no health effects, bitter taste, or scaling problems (DWAF, 1996b). In a study on greywater re-use in SA, Murphy (2006) found that Mg concentrations were higher in kitchen sink water than in bathwater. This may explain the slightly higher concentrations of the metal in the MO-AW and the N-AW influent and effluent compared with that of the Z-AW. Therefore, although there were no significant changes in these parameters for the MO-AW and Z-AW systems pre- and post-treatment, the concentrations were low enough to begin with for the greywater to be suitable for use in irrigation.

Sodium (Na) is present in detergents and laundry soaps as a counter ion, and can therefore be expected to be found in high quantities in greywater containing laundry effluent (Rodda *et al*., 2010). The concentration of Na in greywater post-treatment for all three CW was lower than the TWQR of the WQG/I as recommended by DWAF (1996a) (Table 24). The SAR provides an indication of the potential for ions such Na present in greywater, to induce sodicity in soil, and negatively impact soil structure (Rodda *et al*., 2010). An increase in the SAR value of soils may indicate a reduction in infiltration rate, permeability, and hydraulic EC of soils, and an increase in hard-setting (poor tilth and difficult cultivation conditions) (DWAF, 1996a). The SAR is calculated as follows (DWAF, 1996a):

SAR = [Na]/([Ca]+[Mg])0.5 (note that these parameters are measured in mmol/L).

The SAR was calculated for each CW, after converting the values from mg/L into mmol/L and using the mean (± SE) values for each system before and after treatment. The SAR value for all systems after treatment was below the recommended value of < 2.0 (as per Rodda *et al*., 2010) (Table 31). This suggests that treated greywater from these systems would have no negative effects on soil structure, sodicity, permeability, hydraulic EC or infiltration rate as a result of the concentrations of Na, Ca, and Mg present in the water.

The concentration of major ions in greywater, such as SO_4 and Cl are used to characterize salts in greywater, which can accumulate in soil if water is used for irrigation (Rodda *et al*., 2010). Chlorine (Cl) is relatively non-toxic at smaller concentrations and can be used by plants as a micro-nutrient (Rodda *et al*., 2010). The presence of anions such as SO_4 is highest in laundry greywater where powdered detergents have been used (Singh *et al*., 2010). Generally, the higher the concentration of salts such as Ca, Mg, Na, SO_4, and Cl, the less suitable the greywater is for irrigation (Murphy, 2006).

Pollutants such as these may also form scum in hard water and may persist for some length of time before being degraded (Madungwe and Sakuringwa, 2007). Sulphates (SO_4) are removed from greywater through the activity of SO_4-reducing bacteria present as part of microbial biofilm assemblages in CW (Mthembu *et al.,* 2013). Sub-surface flow (SSF) CW are ideal for the growth of bacteria, which are essential to the removal of pollutants from wastewater (Saeed and Sun, 2012). As SSF CW are permanently submerged, aerobic conditions only occur around plant roots and on plant root surfaces, leaving much of the system in an anaerobic state. This is suitable for processes such as denitrification and SO_4 reduction (Mthembu *et al*., 2013). Sulphates (SO_4) in greywater may also provide beneficial nutrients for plant growth at acceptable concentrations (Rodda *et al*., 2010).

Table 31. Sodium adsorption rates (SAR) calculated for greywater pre- and post-treatment by three CW (as per DWAF, 1996b).

CW	Pre-treatment SAR value	Post-treatment SAR value
MO-AW	2.40	1.14
N-AW	2.35	1.41
Z-AW	0.96	0.50

5.7. Changes in physical water quality parameters

The concentration of TDS in greywater refers to the amount of inorganic salts dissolved in water (Murphy, 2006) and is measured as the mass of dissolved inorganic and organic compounds in water (DWAF, 1996a). The major ions that cause an increase in TDS in greywater include Na, K, Ca, Mg, and Cl (Rodda *et al*., 2010). Electrical conductivity (EC), measured as the ability of water to conduct an electrical current, is directly proportional to TDS (DWAF, 1996). In this study, the concentration of TDS significantly increased in post-treatment greywater for the MO-AW (Figure 15), even though there was only a 29% difference in concentration pre- and post-treatment. There was no significant change in EC pre- and post-treatment for the MO-AW (Table 12), although there was a 27% increase in the value post-treatment. For the N-AW, there was a 31% significant increase in TDS post-treatment (Table 16), and a significant increase in EC post-treatment (Figure 23). Pescod (1992), suggested that an increase in TDS can result from high evaporation rates, causing an increase in salt concentration or a drop in pH from a more alkaline to neutral state, which causes salts like $CaCO_3$ to precipitate out. There was a non-significant decrease in EC and TDS pre- and post-treatment for the Z-AW, with a 21% and 13% decrease post-treatment, respectively (Table 20). The overall mean (± SE) of TDS (mg/L) in this study was high (303.28 ± 20.74 mg/L) compared to the TWQR for WQG/I (DWAF, 1996a). However, TDS concentrations of greywater in this study were similar to those found in other studies, both pre- and post-treatment i.e. between 130 and 1 500 mg/L for pre-treated greywater, and on average 315 mg/L for post-treatment greywater (Eriksson *et al.*, 2002; Engelbrecht and Murphy, 2006; Roesner *et al*., 2006; Al-Hamaiedeh and Bino, 2010; Rodda *et al*., 2010; Mandal *et al*., 2011; Ghaitidak *et al*., 2013). The TWQR for EC and TDS is < 40 mg/L, while a value of 270-540 mg/L suggests Class 3 water; a 90% yield of moderately salt-sensitive crops can be maintained but irrigation of the foliage of sensitive crops should be avoided (DWAF, 1996). A high concentration of TDS can create an accumulation of salt in the soil if the water is used for irrigation, and can lead to a decrease in plant productivity (Rodda *et al*., 2010). Decreased plant productivity as a result of high concentrations of TDS is a result of the effect of dissolved salts on the osmotic potential of soil water; an increase in TDS causes an increase in osmotic pressure, which means plants need to expend more energy to absorb water. This creates a decline in plant productivity (Pescod, 1992). Zhang (2012), noted that typically untreated wastewater can show weak, medium, and strong concentrations of TDS, where a weak value is 250 mg/L, a medium value is 500 mg/L and a strong value is 850 mg/L (Zhang, 2012). The mean TDS value recorded in this study falls slightly higher than the weak value as stated by Zhang (2012). The presence of high concentrations of TDS in wastewater can have potentially negative effects on human, plant, and soil health as it can increase salinity, and toxicity in plants, and can cause issues with soil permeability (World Water Assessment Programme (WWAP), 2017).

There was a significant decrease in turbidity between pre- and post-treatment greywater for the MO-AW and for the N-AW, with an 87% and 78% reduction in turbidity, respectively (Table 27). Turbidity affects water clarity and changes in colour, and is caused by suspended matter such as clay, silt, inorganic and organic matter, and other microorganisms (Dallas and Day, 2004). Turbidity in water can affect the presence of metals and nutrients in water, and can cause an increase in microbial growth (DWAF, 1996c). In addition, high turbidity, generally found in kitchen and washing machine greywater, can cause clogging of soil pores that then affects water infiltration and percolation (Morel, 2005). Turbidity is closely related to the amount of SS in greywater, or total suspended matter, which is the amount of inorganic and organic matter suspended in water; it is the measure of the concentration of SS as a result of the light-scattering ability of water (DWAF, 1996b). High turbidity in greywater, specifically kitchen greywater, may occur as a result of soap and food particles (Bakare *et al*., 2017). The turbidity of the MO-AW and N-AW greywater, which contained wastewater from the kitchen, was significantly higher pre-treatment than the Z-AW (Table 21), which did not contain kitchen wastewater. Li *et al*. (2009), showed that the biological processes that occur in CW and membrane bioreactors are very efficient in the removal of turbidity from greywater. It is possible that some of the greywater may not have passed through the filtration system, according to an explanation by Frazer-Williams (2007), and thus showed higher concentrations of turbidity as a result of increased SS. The level of turbidity in the water can be related to the amount of SS present, but this depends on the nature and particle size of the SS (DWAF, 1996b).

Dissolved oxygen (DO) is the amount of oxygen dissolved in water and therefore available for aquatic organisms; low concentrations of DO may indicate water pollution, specifically organic pollution (Carden *et al*., 2007). Dissolved oxygen (DO) concentration in water is primarily determined by dissolved solids, temperature, and biological activities (Katsenovich *et al*., 2009). Low concentrations of DO can cause an increase of the dissolution in water of nutrients and toxic salts and metals such as NH_3, Cl, copper (Cu), chromium (Cr), cyanide (Cn), Pb, and manganese (Mn) (DWAF, 1996a). It must be noted that greywater that is stored for more than 48 hours can show a decline in DO (Eriksson *et al*., 2020) as a result of biodegradation of organic matter. Wu *et al.* (2016), noted that other studies have shown a correlation between the die-off or removal of faecal bacteria and the increase in DO but further research is required. Dissolved oxygen (DO) can be replaced in water through oxygen transfer via plant root oxygen release or atmospheric diffusion (Chan, 2013). Lv *et al*. (2017), showed that CW planted with macrophytes presented higher DO concentrations than unplanted CW. There was a significant increase in DO values post-treatment for the Z-AW only (Table 20), with a 50% improvement. There were non-significant increases in DO post-treatment of 28% and 9% for the MO-AW (Table 12) and N-AW (Table 16), respectively. Overall, DO concentrations pre-treatment were between 1.2 and 1.8 mg/L, while post-treatment values were between 1.3 and 2.8 mg/L (Table 27). The pre-treatment DO concentrations in this study are slightly lower compared with other similar research (Carden *et al*., 2007). Low DO concentrations may be a result of the saturated and therefore anaerobic conditions of the HSSF CW in this study. Algal growth facilitated by the presence of nutrients can also cause a decrease in DO concentrations (Shukla *et al*., 2008). The increase in DO post-treatment could be attributed to the addition of oxygen into the water via plant root exchange (Chan, 2013). Frazer-Williams *et al*. (2007), also noted that DO can increase with movement of water through a treatment system.

Values of pH generally cause issues when they are extremely acidic or extremely basic. Soil pH can affect the population of microorganisms in the soil and plant health, as well as the availability of heavy metals and nutrients (Rodda *et al*., 2010). The pH level of greywater suitable for irrigation is between 6.5 and 8.4, allowing for unrestricted use of greywater for irrigation with little to no negative effects on human health, or on soil and plant conditions (Rodda *et al*., 2010). The pH concentration of all three CW in this study, post-treatment, fell within the parameters set for unrestricted use (Table 29), and were similar to those measured in other studies (Table 30).

5.8. Efficient designs for constructed wetlands (CW)

The efficiency of CW is determined mainly by plant selection, substrate selection, water depth, hydraulic loading rate (HLR), and HRT (Wu *et al*., 2015). Systems with a longer HRT are able to develop appropriate microbial communities and provide adequate time for pollutants to be removed (Wu *et al*., 2015). Longer retention times allow for greater adsorption of pollutants (Leong *et al*., 2017). Wu *et al*. (2015), assessed design characteristics of CW to determine the optimal criteria for efficient CW operations (Table 32).

Table 32. Recommended design criteria for the optimal performance of SSF CW for the treatment of greywater (adapted from Wu et al., 2015), in comparison with the CW designs for this research project (Wolmarans, 2017).

Parameters	**Design criteria**	
	Wu *et al.* (2015)	Wolmarans (2017)
Bed size (m^2)	< 2 500	6
Water depth (m)	0.4 - 1.6	0.5
Hydraulic slope (%)	0.5 - 1	0.5
Media	Natural media with a porosity of 0.3 - 0.5, particle size of < 20 mm.	Particle size of 10 - 60 mm
Vegetation	Native species preferred, plant density must give 80% coverage	Indigenous species suitable to Highveld climatic conditions
HRT (day)	2 - 5	4
Length to width ratio	< 3:1	1.6

The HRT for this study's CW was four days as determined by Wolmarans (2017). This falls within the recommended HRT as suggested by Wu *et al.* (2015). Hydraulic retention time (HRT) may be influenced by the dominant plant species grown in a system, as well as temperature, both which affect the hydraulic efficiency of wetlands (Wu *et al*., 2015). The depth of water in SSF systems influences the redox status of the system, which affects the biochemical reactions that allow the degradation of organic matter. Systems with a shallow water depth of 0.27 m as opposed to 0.5 m are generally more efficient at treating greywater (García *et al*., 2005). This study's media particle size was slightly bigger than recommended (Table 26). García *et al.* (2005), found that SSF systems with fine gravel substrate (3.5 mm in size) produced treated water of a higher quality than those with course gravel substrate (10 mm in size). However, substrate clogging over time, which occurs at a faster rate in systems with finer media, can lead to a shortening of the life span of the system (Wu *et al*., 2015).

It is suggested that the volume of greywater influent was too high for the capacity of this study's wetland design. The design was to accommodate a family of four people, based on the A/NZ standards for on-site domestic wastewater management (2000) at a rate of approximately 200 litres per day. As the flow velocity of the greywater influent in this study was too low to be monitored with a domestic water meter, the amount of wastewater entering the wetlands could not be accurately measured. However, based on the number of people utilising the facilities, it was estimated that each system received wastewater from an average of 15 people. This included washing of dishes in the kitchen (an average of 10 litres per load), washing of hands in the toilet basins (at an average of 2 litres/minute), and showering (at an average of 22 litres/minute) (Cape Town Green Map, *n.d.*).

General observation noted that, per system, on average, eight sinks of water were used per kitchen per day to wash dishes. This equates to approximately 80 litres of greywater a day. Hands were washed approximately 45 times for approximately 10 seconds a time, within a day in total for both male and female bathrooms, and generally 7 showers were taken every day in total for an average of 10 minutes a shower, including male and female bathrooms. On average, approximately 175 litres of greywater was produced per day for the MO-AW, 515 litres a day for the N-AW, and 1 115 litres a day for the Z-AW. In comparison with the standards used to design the systems, only the MO-AW fell within the volume requirements, while the N-AW and Z-AW's greywater influent was much higher than recommended. At times it was observed that untreated effluent was pooling on the surface of the CW media, specifically for the N-AW and Z-AW CW. This may be a result of excessive volumes of wastewater that may have overwhelmed the capacity of the system, or a result of rainfall events.

Wu *et al*. (2015), found that 'continuous feeding' of greywater into CW is not as efficient as 'batch feeding', which promotes greater oxidation, while 'intermittent feeding' increases the rate of removal of organics and N. Intermittent feeding refers to the delivery of varying amounts of collected wastewater into a CW daily, for a certain period of time e.g. 20 minutes, while continuous feeding is the continuous delivery of wastewater into the CW (Caselles-Osorio and García, 2007). Intermittent feeding causes greater internal turbulence and mixing as influent is poured into the CW and allows the wastewater to come into contact with both aerobic and anaerobic microsites, increasing treatment efficiency (Caselles-Osorio and García, 2007). Mthembu *et al.* (2013), also suggested that CW need to be fully established first in order to allow macrophytes and biofilms to function efficiently before maximum contaminant removal can be expected.

Overall, the systems in this study were efficient at decreasing concentrations of pollutants such as PO_4, turbidity, TDS, oil and grease, SO_4, B, organic carbon, and *E. coli*. It must be noted that the concentrations of *E. coli* in the greywater both pre- and post-treatment, were very high and may cause negative health effects if the greywater is used for domestic purposes. It is recommended that further treatment to remove pathogenic organisms be applied to the greywater effluent before use as irrigation in the garden.

5.9. Limitations to study design

There were a number of limitations to the design and application of the systems, which may have affected the systems' efficiency at removing pollutants from greywater.

- It is possible that the wetlands were too small to accommodate the greywater produced by the number of people based at each site;
- The wetlands were constructed in the winter month of July 2017. This may have reduced the growth rate of the microbes and aquatic vegetation, thereby reducing the efficiency of the systems and preventing them from treating the greywater as effectively as expected. It is recommended that the wetlands are left for a period of 3 months to allow them to establish and settle before used to treat greywater;
- The sampling points pre- and post-treatment were open to the environment, which may have led to the introduction of pollutants such as soil and organic matter into the treated effluent; and
- The post-treatment effluent was allowed to stand at the sampling points within the PVC pipes for a number of days between sampling events. This may have affected the pollutant load, specifically the bacterial counts in the water.

This research has highlighted a number of difficulties and the complexity of the sampling programme, as well as the sampling points within the system. Refinement of the systems' designs and sampling programmes may lead to a more comprehensive and accurate understanding of the systems' efficiency at treating domestic greywater.

Chapter 6: Conclusions and recommendations

6.1. Conclusions

The re-use of greywater has been driven by global issues such as resource depletion, climate change, and the need for a more sustainable lifestyle (Eriksson *et al*., 2010). There are a number of benefits of using greywater for small-scale agricultural and garden irrigation such as its use in areas where the availability of water and plant nutrient supplementation is low; the ability to irrigate gardens and crops during times of drought; and the reduction on the demand of freshwater supplies from local authorities (Rodda *et al*., 2010). Constructed wetlands (CW) provide effective water treatment systems with minimal costs related to maintenance, operation, and energy requirements (Katsenovich *et al*., 2009). Sub-surface flow (SSF) CW are efficient at removing organics, SS, microbial pollution, and heavy metals, and are less sensitive to cold temperatures (Wu *et al*., 2015). Brix and Schierup (1989), note that macrophyte-based CW systems are efficient for use in locations with low effluent loads, such as small industries, single households, and small villages.

The study addressed one hypothesis, namely:

Null hypothesis (H_0)

Constructed wetlands (CW) can effectively treat household greywater by significantly reducing contaminants to a standard suitable for re-use in activities that require non-potable water, such as garden irrigation.

Alternative hypothesis (H_1)

There is no significant difference in the water quality of household greywater before and after treatment with CW.

The null hypothesis is accepted. Constructed wetlands (CW) analysed in this study, significantly reduced the concentration of certain contaminants in treated greywater to within the range suitable for irrigation using drip systems, as prescribed by the TWQR for the WQG/I (DWAF, 1996a). The only concern was the reduction in *E. coli* counts, whereby the post-treatment concentrations of all three CW were above the recommended TWQR for WQG/I (DWAF, 1996a). The CW used for the treatment of greywater are easily constructed using locally available materials that can be sourced at various hardware and outdoor stores. The CW were designed in such a way that they can be constructed by the homeowner.

The primary aim of this research was to test the effectiveness of three small-scale CW on the treatment of greywater from different sources, namely, kitchen sink, bathroom basin, and shower greywater. Water quality was measured before and after the greywater was passed through the CW to compare for various water quality parameters such as DO, turbidity, pH, metals, and oil and grease, amongst others. A comparison between the water quality before and after treatment provided information on the suitability of CW for the treatment of household greywater, specifically for use in irrigation of urban gardens. Secondly, the need to adopt Water Wise behaviours such as the re-use of household greywater, will be communicated to members of the public through the promotion of a manual detailing the construction of CW for the treatment of greywater.

The primary aim was met by taking samples of greywater influent (before treatment) and treated greywater effluent (after treatment). The samples were then analysed for twenty-one water quality parameters at Rand Water's laboratory. Results were analysed using various statistical tests to compare the efficiency of the CW treatment functions.

Four objectives were set for this study:

Objective 1: Implement three CW on site at Rand Water's Environmental Management Services Department that are easy to construct, at locations that are accessible for the treatment of typical 'household-type' greywater such as kitchen sink, bathroom basin, and shower greywater.

Three CW were designed and constructed on site at Rand Water's Environmental Management Services department in 2017, as discussed in section 3.3 of Chapter 3. Each CW was strategically placed to directly receive greywater from kitchen sinks, bathrooms basins, and showers.

Objective 2: Collect samples of the greywater before and after treatment by CW. Analyse the samples for various water quality parameters.

Samples were taken of greywater influent i.e. untreated greywater, before it passed through the CW, as per section 3.5 of Chapter 3. Samples were then taken of the greywater effluent i.e. treated greywater once it had passed through the CW. Water quality samples were collected as per the Rand Water Analytical Services Sampling Procedure for Biology and Chemistry 3.3.1.10.1 (2017).

Objective 3: Use the results of the water quality analyses to determine if the CW significantly reduce the concentration of contaminants in greywater, or improve water quality, to indicate the effectiveness of the wetlands to 'treat' greywater to a standard suitable for re-use in garden irrigation.

The TWQR prescribed by the WQG/I (DWAF, 1996a), were used as a benchmark against which certain greywater water quality parameters were measured. These parameters were B, Cl, DO, *E. coli*, N, Na, TDS, temperature, turbidity, and TP. For all CW, greywater quality post-treatment fell below the TWQR prescribed by the WQG/I, except for *E. coli*. Water quality guidelines for other parameters such as oil and grease, pH, and SAR were benchmarked against guidelines for water quality of greywater for irrigation of small-scale crops and food gardens as prescribed by Rodda *et al.* (2010). Treated greywater for all CW fell below the SAR prescribed by Rodda *et al*. (2010). The results of these analyses can be found in Chapter 4.

Objective 4: Develop a manual for the assembly of small-scale CW that can be set up easily by residential home owners. This manual will be used in future awareness and education campaigns to promote the use of CW to treat household greywater.

A manual was designed and developed, highlighting the materials and methods required to construct these CW. The manual can be found in Appendix A. The manual will be made available to the public for free once this dissertation is submitted, through an awareness campaign to be run by the Water Wise team.

6.2. Recommendations

The following recommendations are provided and divided into sections specific to CW design, end users, and future research:

The CW design tested in this study showed that treatment efficiency was not as effective as suggested by various literature, specifically for the decrease in *E. coli* counts (as per Erikkson *et al*., 2002; Rodda *et al*., 2010; Ghunmi *et al*., 2011; Wu *et al*., 2016). Therefore, the following recommendations refer to the improvement of CW design and treatment efficiency:

- Increase the surface size of the system or reduce the volume of influent to prevent overloading the system's capacity;
- Allow for a longer retention time;

- Aerate the system to increase treatment efficiency. Aeration can be done by pumping greywater into the system (Hyun *et al*., 2016) instead of allowing it to trickle through the inlet pipe passively;
- Trial the use of different macrophyte species and species compositions; and
- Trial the use of different sized substrate.

Objective 4 refers to the development of a manual to allow the end-user to implement small-scale CW in a domestic setting. The following recommendations refer to the end-user:

- Allow the system to settle or establish for a minimum of three months before introducing greywater into the system;
- Remove and clean the gravel substrate with tap or rainwater every 5-10 years to ensure the efficiency of the CW;
- Maintain the macrophyte species grown in the CW by cutting back plant growth every winter to stimulate summer growth;
- Utilise the manual developed to assist with the correct implementation of the CW; and
- Encourage the implementation of CW in all new housing developments.

Further research on CW efficiency for greywater treatment is recommended as follows:

- Close off all sample points at the inlet and outlet of the CW to prevent potential environmental contamination of the samples;
- Limit the time that treated greywater is left to stand before samples are taken;
- Investigate different species of macrophytes, such as *Typha capensis*, as recommended in the literature (Vymazal, 2011) to enhance CW treatment efficiency;
- Investigate potential errors in the design of CW that prevent the effective reduction in *E. coli* counts in the treatment of greywater;
- Research the long-term (5-10 years) efficiency of CW in greywater treatment;
- Develop a set of standards or guidelines for the use of CW for greywater treatment in conjunction with research institutions such as the Water Research Commission, and green industry specialist such as the South African Landscape Institute, specifically for small-scale CW for domestic use.

Chapter 7: References

Al-Hamaiedeh, H. and Bino, M. (2010). Effect of treated greywater re-use in irrigation on soil and plants. *Desalination* 256: 115-119.

Al-Jayyousi, O.R. (2003). Greywater re-use: towards sustainable water management. *Desalination* 156: 181-192.

Arden, S. and Ma, X. (2018). CW for greywater recycle and re-use: A review. *Science of the Total Environment* 630: 587-599.

Australia / New Zealand Standard (2012). *On-site domestic wastewater management*. Report No. S/NZS 1547:2012. ISBN: 978-1-86975-236-1.

Avery, L.M., Frazer-Williams, R.A.D., Winward, G., Shirley-Smith, C., Liu, S., Memon, F.A. and Jefferson, B. (2007). CW for greywater treatment. *Ecohydrology and Hydrobiology* 7 (3-4): 191-200.

Ayaz, S.Ç., Aktaş, O., Fındık, N. and Akca, L. (2012). Phosphorous removal and effect of adsorbent type in a constructed wetland system. *Desalination and Water Treatment* 37 (1-3): 152-159.

Bakare, B.F., Mtsweni, S. and Rathilal, S. (2017). Characteristics of greywater from different sources within households in a community in Durban, South Africa. *Journal of Water Re-use and Desalination* 7 (4): 520-528.

Bean, C. and Yang, C-H. (2009). Standards in Sustainable Landscape Architecture. UTSoA – Seminar in Sustainable Architecture. Student paper for Sustainable Design Seminar/Studio, University of Texas, United States of America.

Benami, M., Busgang, A., Gillor, O. and Gross, A. (2016). Quantification and risks associated with bacterial aerosols near domestic greywater-treatment systems. *Science of the Total Environment* 562: 344-352.

Bertino, A. (2010). *Study on One-stage Partial Nitritation-Anammox Process in Moving Bed Biofilm Reactors: a Sustainable N Removal*. Unpublished Masters' dissertation. Politecnico di Torino, Italy and Royal Institute of Technology, Sweden.

Birks, R. and Hills, S. (2007). Characterisation of indicator organisms and pathogens in domestic greywater for recycling. *Environmental Monitoring and Assessment* 129 (1-3): 61-69.

Blumenthal, U.J., Mara, D.D., Peasey, A., Ruiz-Palacios, G. and Stott, R. (2000). Guidelines for the microbiological quality of treated wastewater used in agriculture: recommendations for revising WHO guidelines. *Bulletin of the World Health Organization* 78 (9): 1104-1116.

Botai, C.M., Botai, J.O., Dlamini, L.C., Zwane, N.S. and Phaduli, E. (2016). Characteristics of droughts in South Africa: a case study of Free State and North West provinces. *Water* 8: 439-462.

Brix, H., and Schierup, H.H. (1989). The use of macrophytes in water pollution control. *AMBIO* (180: 100-107.

Browning, J. (1991). Studies in Cyperaceae in southern Africa. 18: A re-appraisal of *Schoenoplectus corymbosus*. *South African Journal of Botany* 57 (6): 335-3443.

Cape Town Green Map (2016, January 26). Baths, showers, geysers, taps and washing machines. Available from <http://www.capetowngreenmap.co.za/go-green/baths-showers-geysers-taps-washing-machines>

Carden, K., Armitage, N., Sichone O. and Winter, K. (2007b). Management options for the safe use and disposal of greywater in the non-sewered areas of South Africa: Part 2 – greywater management options. *Water SA* 33 (4): 433-442.

Carden, K., Armitage, N., Winter, K., Sichone, O. and Rivett, U. (2007a). Understanding the use and disposal of greywater in the non-sewered areas in South Africa. *WRC Report No.* 1524/1/07. ISBN: 978-1-77005-525-4.

Caselles-Osorio, A. and García, J. (2007). Impact of different feeding strategies and plant presence on the performance of shallow horizontal sub-surface-flow CW. *Science of the Total Environment* 378 (3): 253-262.

Chan, C. (2013). *An investigation into CW for domestic greywater treatment and re-use in Ontario.* Unpublished Masters' dissertation. University Guelph, Canada.

Chihomvu, P. Stegmann, P. and Pillay, M. (2014). Identification and characterization of heavy meal resistant bacteria from the Klip River. *International Journal of Biological, Biomolecular, Agricultural, Food and Biotechnological Engineering* 8 (11): 1178-1188.

Chihomvu, P. Stegmann, P. and Pillay, M. (2015). Characterization and Structure Prediction of Partial Length Protein Sequences of *pcoA, pcoR* and *chrB* Genes from Heavy Metal Resistant Bacteria from the Klip River, South Africa. *International Journal of Molecular Science* 16 (4): 7352-7374.

Cho, K.H., Han, D., Park, Y., Lee, S.W., Cha, S.M., Kang, J.H. and Kim, J.H. (2010). Evaluation of the relationship between two different methods for enumeration faecal indicator bacteria: colony-forming unit and most probable number. *Journal of Environmental Sciences* 22 (6): 846-850.

Dallas, H.F. and Day, J.A. (2004). The effect of water quality variables on aquatic ecosystems: a review. *WRC Report No*. TT 224/04.

Department of Water Affairs and Forestry (DWAF) (1996b). *South African Water Quality and Guidelines (second edition). Volume 1: Domestic Use*. DWAF, Pretoria, South Africa. ISBN: 0-7988-5342-5.

Department of Water Affairs and Forestry (DWAF) (1996a). *South African Water Quality and Guidelines (second edition). Volume 4: Agricultural Use: Irrigation*. DWAF, Pretoria, South Africa. ISBN: 0-7988-5342-5.

Department of Water Affairs and Forestry (DWAF) (1996c). *South African Water Quality and Guidelines (second edition). Volume 4: Agricultural Use: Aquaculture*. DWAF, Pretoria, South Africa. ISBN: 0-7988-5342-5.

Department of Water Affairs and Forestry (DWAF) (1996d). *South African Water Quality and Guidelines (first edition). Volume 8: Field Guide*. DWAF, Pretoria, South Africa. ISBN: 0-7988-5346-8.

Department of Water Affairs and Forestry (DWAF) (1997). Water Services Act No. 108 of 1997. Department of Water Affairs and Forestry, Pretoria.

Department of Water Affairs and Forestry (DWAF) (2005). *A practical field procedure for identification and delineation of wetlands and riparian areas, Edition 1*. Department of Water Affairs and Forestry, Pretoria.

Donner, E., Eriksson, E., Revitt, M., Scholes, L., Holten Lützhøft, H-C. and Ledin, A. (2008). *Water Framework Directive Priority Substance dynamics in treatment and re-use systems for domestic greywater*. 11th International Conference in Urban Drainage, Edinburgh, Scotland, UK, 2008.

Doughten, R. (2010). *Recommendations on greywater treatment, disposal and re-use.* Report No. DEQ 10-WQ-026. Department of Environmental Quality (DEQ), State of Oregon.

Driver, A., Nel, J.L, Snaddon, K., Murray, K., Roux, D.J., Hill, L., Swartz, E.R., Manuel, J. and Funke, N. (2011). Implementation Manual for Freshwater Ecosystem Priority Areas. *WRC Report No*. 1801/1/11. ISBN: 978-1-4312-0147-1.

Ecosan Services Foundation (ESF) (2008). *Small-scale CW for greywater and total domestic wastewater treatment*. Version 1, 14 March 2008, Switzerland.

Engelbrecht, J.F.P. and Murphy, K. O'H. (2006). *What stops me from using greywater?* A paper presented at the WISA conference in Durban, May 2006. Unpublished.

Environmental Protection Agency (EPA) (2012). Guidelines for Water Re-use. United States Environmental Protection Agency, *EPA* 600-R-12-618, September 2012.

Environmental Protection Agency (EPA) (1993). Sub-surface flow CW for wastewater treatment: a technology assessment. United States Environmental Protection Agency, *EPA* 832-R-93-008, July 1993.

Environmental Protection Agency (EPA) (2000). Wastewater Technology Fact Sheet. Wetlands: Sub-surface flow. United States Environmental Protection Agency, *EPA* 832-F-00-023, September 2000.

Erikkson, E., Auffarth, K., Henze, M. and Ledin, A. (2002). Characteristics of grey wastewater. *Urban Water* 4: 85-104.

Finley, S., Barrington, S. and Lyew, D. (2009). Re-use of domestic greywater for the irrigation of food crops. *Water, Air and Soil Pollution* 199: 235-245.

Fraser, L.H., Carty, S.M. and Steer, D. (2004). A test of four plant species to reduce total N and total phosphorus from soil leachate in sub-surface wetland microcosms. *Bioresource Technology* 94 (2): 185-192.

Frazer-Williams, R.A.D. (2007). CW for Advanced Treatment and Re-use. Unpublished doctoral thesis. Cranfield University, UK.

García, J., Aguirre, P., Barragán, J., Mujeriego, V.M. and Bayona, J.M. (2005). Effect of key design parameters on the efficiency of horizontal sub-surface flow CW. *Ecological Engineering* 25: 405-418.

Gemmell, M. and Schmidt, S. (2010). Potential links between irrigation water quality and microbiological quality of food in subsistence farming in KwaZulu-Natal, South Africa. In: *Current Research, Technology and Education Topics in Applied Microbiology and Microbial Biotechnology* (pp. 1190-1195). Edited by Méndez-Vilas, A. Formatex Research Centre. ISBN: 8-4614-6195-9.

Ghaitidak, D.M. and Yadav, K.D. (2013). Characteristics and treatment of greywater – a review. *Environmental Science and Pollution Research* 20: 2795-2809.

Ghunmi, L.A., Zeeman, G., Fayyad, M. and van Lier, J.B. (2011). Greywater treatment systems: a review. *Critical Reviews in Environmental Science and Technology* 41: 657-698.

Google Earth Pro (2016). Rand Water Environmental Management Services Department site (26°21′08″S;28°04′02″E), elevation 170 M. Viewed 22 December 2017. <http://www.google.com/earth/index.html>.

Gross, A., Azulai, N., Oron, G., Ronen, Z., Arnold, M. and Nejidat, A. (2005). Environmental impact and health risks associated with greywater irrigation: a case study. *Water Science and Technology* 52 (8): 161-169.

Gross, A., Shmueli, O., Ronen, Z. and Raveh, E. (2007). Recycled vertical flow CW (RVFCW) – a novel method of recycling greywater for irrigation in small communities and households. *Chemosphere* 66: 916-923.

Hach Company (n.d.). *Corrosion Management Manual: Test Kit Model CM-1*. Printed by Hach Company World Headquarters, Colorado, USA.

Hoffmann, H., Platzer, C., Winker, M. and Von Muench, E. (2011). *Technology review of CW: sub-surface flow CW for greywater and domestic wastewater treatment.* Sustainable sanitation – EFS program, Germany.

Humphries, M.S., McCarthy, T.S. and Pillay, L. (2017). Attenuation of pollution arising from acid mine drainage by a natural wetland on the Witwatersrand. *South African Journal of Science* 113 (1/2): 1-9.

Hyun, K., Choia, J., Kib, D., Park, J., Ahn, S., Oh, H. and Choung, Y-K. (2016). Bathroom wastewater treatment in CW with planting, non-planting and aeration, non-aeration conditions. *Desalination and Water Treatment* 57: 709-717.

Ilemobade, A.A., Olanrewaju, O.O. and Griffioen, M.L. (2012). Greywater re-use for toilet flushing in high-density urban buildings in South Africa: a pilot study. *WRC Report No*. 1821/1/11. ISBN: 978-1-4312-0213-3.

Jasper, J.Y., Nguyen, M.T., Jones, Z.L., Ismail, N.S., Sedlak, D.L., Sharp, J.O., Luthy, R.G., Horne, A.J. and Nelson, K.L. (2013). Unit Process Wetlands for Removal of Trace Organic Contaminants and Pathogens from Municipal Wastewater Effluents. *Environmental Engineering Science* 30 (8): 421-436.

Jokerst, A.W., Roesner, L.A. and Sharvelle, S.E. (2009). An evaluation of greywater re-use utilising a CW treatment system. World Environmental and Water Resources Congress, 2009.

Karathanasis, A.D., Potter, C.L. and Coyne, M.S. (2003). Vegetation effects on fecal bacteria, BOD, and suspended solid removal in CW treating domestic wastewater. *Ecological Engineering* 20: 157-169.

Katsenovich, Y.P., Hummel-Batista, A., Ravinet, A.J. and Miller, J.F. (2009). Performance evaluation of CW in a tropical region. *Ecological Engineering* 35: 1529-1537.

Kleyhans, C.J., Thirion, C. and Moolman, J. (2005). *A level 1 River Ecoregion Classification System for South Africa, Lesotho, and Swaziland*. Report No. N/0000/00/REQ0104. Resource Quality Services, Department of Water Affairs and Forestry, Pretoria, South Africa.

Kotze D.C., Marneweck G.C., Batchelor A.L., Lindley D.S. and Collins N.B. (2007). *WET-EcoServices: A technique for rapidly assessing ecosystem services supplied by wetlands.* WRC Report No TT 339/08, Water Research Commission, Pretoria.

Laaffat, J., Ouazzani, N. and Mandi, L. (2015). The evaluation of potential purification of a horizontalusbsurface flow CW treating greywater in a semi-arid environment. *Process Safety and Environmental Protection* 95: 86-92.

Lakay, V.M. (2012). *An analysis of the performance of CW in the treatment of domestic wastewater in the Western Cape, South Africa*. Unpublished Masters' dissertation. University of Cape Town, South Africa.

Leong, J.Y.C., Chong, M.N. and Poh, P.E. (2017). Assessment of greywater quality and performance of a pilot-scale decentralised hybrid rainwater-greywater system. *Journal of Cleaner Production* 172: 81-91.

Li, F., Wichmann, K. and Otterpohl, R. (2009). Review of the technological approaches for greywater treatment and re-use. *Science of the Total Environment* 407: 3439-3449.

Ling, T-Y., Apun, K. and Zainuddin, S-R. (2009). Performance of a pilot-scale biofilter and CW with ornamental plants in greywater treatment. *World Applied Sciences Journal* 6 (11): 1555-1562.

Liu, R., Zhao, Y., Doherty, L., Hu, Y. and Hao, X. (2015). A review of incorporation of CW with other treatment processes. *Chemical Engineering Journal* 279: 220-230.

Lv, T., Carvalho, P.N., Zhang, L., Zhang, Y., Button, M., Arias, C.A., Weber, K.P. and Brix, H. (2017). Functionality of microbial communities in CW used for pesticide remediation: Influence of system design and sampling strategy. *Water Research* 110: 241-251.

Madungwe, E. and Sakuringwa, S. (2007). Greywater re-use: a strategy for water demand management in Harare? *Physics and Chemistry of the Earth* 32: 1231-1236.

Maimon, A., Fredler, E. and Gross, A. (2014). Parameters affecting greywater quality and its safety for re-use. *Science of the Total Environment* 487: 20-25.

Mandal, D., Labhasetwar, P., Dhone, S., Dubey, A.S., Shinde, G. and Wate, S. (2011). Water conservation due to greywater treatment and re-use in urban setting with specific context to developing countries. *Resources, Conservation and Recycling* 522: 356-361.

Masi, F. (2009). Water re-use and resources recovery: the role of CW in the Ecosan approach. *Desalination* 246: 27-34.

Maupin, A.J. (2011). Presentation on CW. *Idaho Water Re-use Conference.*

Morel, A. (2005). *Greywater treatment on household level in developing countries – a state of the art review*. Swiss Federal Institute of Technology, Zurich.

Mthembu, M.S., Odinga, C.A., Swalaha, F.M. and Bux, F. (2013). CW: a future alternative wastewater treatment technology. *African Journal of Biotechnology* 12 (29): 4542-4553.

Mucina, L., and Rutherford, M.C., (2006). The vegetation of South Africa, Lesotho and Swaziland. Publishers: South African National Biodiversity Institute, Pretoria. ISBN -13: 978-1-919976-21-1.

Mucina, L., Rutherford, M.C. and Powrie, L.W. (2006). The Logic of the Map: Approaches and Procedures. In: *The vegetation of South Africa, Lesotho and Swaziland*. Strelitzia 19. South African National Biodiversity Institute, Pretoria. ISBN -13: 978-1-919976-21-1.

Mukheibir, P. (2005). *Local water resource management strategies for adaption to climate induced impacts in South Africa*. Prepared for the workshop: Rural Development and the role of food, water and biomass: opportunities for development and climate. Novotel, Dakar, November 2005.

Murphy, K.O'H. (2006). A Scoping Study to Evaluate the Fitness-for-Use of Greywater in Urban and Peri-Urban Agriculture. *WRC Report No*. 1479/1/06. ISBN: 1-77005-475-5.

National Water Resource Strategy (NWRS) (2013). Department of Water Affairs, National Water Resource Strategy, 2nd Edition, June 2013.

Okun, D.A. Distributing reclaimed water through dual-systems. *American Water Works Association Journal* 89 (11): 52-64.

Ollis, D.J., Snaddon, C.D., Job, N.M. and Mbona, N. (2013). *Classification System for Wetlands and other Aquatic Ecosystems in South Africa. User Manual: Inland Systems*. SANBI Biodiversity Series 22. South African National Biodiversity Institute, Pretoria.

Paulo, P.L., Azevedo, C., Begosso, L., Galbiati, A.F. and Boncz, M.A. (2013). Natural systems treating greywater and blackwater on-site: Integrating treatment, re-use and landscaping. *Ecological Engineering* 50: 95-100.

Peel, M.C., Finlayson, B.L. and McMahon, T.A. (2007). Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth Systems Sciences* 11: 1633-1644.

Pescod, M.B. (1992). Wastewater treatment and use in agriculture – FAO irrigation and drainage paper 47. *Food and Agriculture Organization of the United Nations.* Rome, Italy. ISBN: 92-5-103135-5.

Petterson, D. (2016, August 16). Dam levels remain a cause for concern. *Infrastructure News and Service Delivery*. Available from: http://www.infrastructurene.ws/2016/08/16/dam-levels-remain-a-cause-for-concern/#

Qomariyah, S., Ramelan, A.H., Sobriyah, A. and Setyono, P. (2016). Use of macrophyte plants, sand and gravel materials in CW for greywater treatment. *Materials Science and Engineering* 176: 1-6.

Quayle, L.M., Dickens, C.W.S., Graham, M., Simpson, D., Goliger, A., Dickens, J.K., Freese, S. and Blignaut, J. (2010). Investigation of the positive and negative consequences associated with the introduction of zero- PO_4 detergents into South Africa. *Water Research Commission Report* No. TT 446/10.

Queensland Government (2008). *Greywater guidelines for plumbers: a guide to the use of greywater in Queensland*. Department of Infrastructure and Planning, Queensland Government, Australia.

Ramprasad, C. and Philip, L. (2016). Surfactants and personal care products removal in pilot scale horizontal and vertical flow CW while treating greywater. *Chemical Engineering Journal* 284: 458-468.

Ramsar Convention on Wetlands (n.d.). *The Ramsar Strategic Plan 2016-2024* (Brochure). Author: the author of the above is the publisher of the brochure.

Ramsar Convention Secretariat (2013). *The Ramsar Convention Manual: a guide to the Convention on Wetlands* (Ramsar, Iran, 1971), 6th ed. Ramsar Convention Secretariat, Gland, Switzerland.

Rand Water (2017). *Sampling Procedure for Biology and Chemistry Work Instruction: 3.3.1.10.1 Rev. No. 04*. Analytical Services, Laboratory Customer Support, Rand Water, South Africa. Pp1-23.

Rodda, M. Carden, K. and Armitage, N. (2010). Sustainable use of greywater in small-scale agriculture and gardens in South Africa: Guidance report. *WRC Report No 469/10*, Water Research Commission, Pretoria, South Africa.

Roesner, L., Qian, Y., Criswell, M., Stromberger, M. and Klein, S. (2006). *Final Report - Long term effects of landscape irrigation using household greywater – literature review and synthesis*. The Water Environment Research Foundation Report No. 03-CTS-18C0.

Saeed, T. and Sun, G. (2012). A review on N and organics removal mechanisms in sub-surface flow CW: Dependency on environmental parameters, operating conditions and supporting media. *Journal of Environmental Management* 112: 429-448.

Schulze, R.E. (1997). *South African Atlas of Agrohydrology and -climatology*. Water Research Commission, Pretoria Report TT82/96.

Schulze, R.E. (2012). A 2011 perspective on climate change and the South African water sector. Water Research Commission, Pretoria Report TT518/12.

Singh, U., Taylor, G., Mhlongo, W., Duys, L., Loxley, C., Townsend, R., Pammenter, N. and Rodda, N. (2010). Effect of powder and liquid laundry detergents on swiss chard plants and soil irrigated with laundry greywater. WISA Biennial Conference 2010, Durban, South Africa.

Shukla, J.B., Misra, A.K. and Chandra, P. (2008). Modeling and analysis of the algal bloom in a lake caused by discharge of nutrients. *Applied Mathematics and Computation* 196: 782-790.

South African National Biodiversity Institute (SANBI) (2013). *Grasslands Ecosystem Guidelines: landscape interpretation for planners and managers*. Compiled by

Cadman, M.,de Villiers, C., Lechmere-Oertel, R. and D. McCulloch. South African National Biodiversity Institute, Pretoria. ISBN: 978-1-919976-88-4.

South African National Biodiversity Institute (SANBI) (2018). SANBI BGIS Map Viewer, Gauteng: C-Plan 3.3. Viewed on 10 January 2018. <http://bgisviewer.sanbi.org/Html5Viewer/Index.html?configBase=http://bgisviewer.sanbi.org/Geocortex/Essentials/REST/sites/Gauteng/viewers/Gauteng/virtualdirectory/Resources/Config/Default&user=sstelli@randwater.co.za&extent=&layerTheme=Gauteng%20C-Plan%203.3%20Terrestestrial%20CBAs>

Srivastava, J., Gupta, A. and Chandra, H. (2008). Managing water quality with aquatic macrophytes. *Reviews in Environmental Science and Biotechnology* 7: 255-266.

Stelli, S., Hoy, L., Hendrick, R. and Taylor, M. (2018). Effects of different mulch types on soil moisture content in potted shrubs. *Water SA* 44 (3): 495-503.

Stelli, S. and Mphomane, M. (2016). Plant health rating scale. *Unpublished*.

Travis, M.J., Weisbrod, N. and Gross, A. (2008). Accumulation of oil and grease in soils irrigated with greywater and their potential role in soil water repellancy. *Science of the Total Environment* 394: 68-74.

Turton, A. (2015). Sitting on the Horns of a Dilemma: Water as a Strategic Resource in South Africa. *@ Liberty: the Policy Bulletin of the IRR*. No. 6 2015/10 November 2015 Issue 22: 1-28.

United Nations (UN) (2012). *United Nations World Water Development Report 4. Volume 1: Managing Water under Uncertainty and Risk. United Nations – Water*, March 2012.

United Nations Economic and Social Council (UNESC) (2017). *Progress towards the Sustainable Development Goals: Report of the Secretary-General*. Report No. 17-07553 (E) 090617.

Van Vuuren, L. (2014, July/August). Mpumalanga wetland rehab partnership a win for ecological infrastructure. *The Water Wheel*: 21-25.

Vasudevan, P., Griffin, P., Warren, A., Thapliyal, A. and Tandon, M. (2011). Localized domestic wastewater treatment: part I - CW (an overview). *Journal of Scientific and Industrial Research* 70: 583-594.

Vermaak, V.M. (2009). *A geomorphological investigation of the Klip River wetland, south of Johannesburg.* Unpublished Masters' dissertation. University of the Witwatersrand, South Africa.

Vymazal, J. (2007). Removal of nutrients in various types of CW. *Science of the Total Environment* 380: 48-65.

Vymazal, J. (2010). CW for wastewater treatment. *Water* 2: 530-548.

Vymazal, J. (2011). Plants used in CW with horizontal sub-surface flow: a review. *Hydrobiologia* 674: 133-156.

Wastewater Gardens (2013). *Information Sheet on CW to Treat Wastewater: Framework and Schematic Overview*. IS202120105.

Wolmarans, L. (2017). *Design and implementation of CW on Rand Water sites to treat greywater – design report*. Report No. J 37031, GIBB Engineering and Architecture. Pp 1-33.

Wong, T.H.F., Breen, P.F., Somes, N.L.G. and Lloyd, S.D. (1999). *Managing Urban Stormwater using CW*. Industry Report No. 98/7. ISBN: 1 876006 36 6.

Wu, S., Carvalho, P.N., Müller, J.A., Manoj, V.R. and Dong, R. (2016). Sanitation in CW: a review on the removal of human pathogens and fecal indicators. *Science of the Total Environment* 541: 8-22.

Wu, H., Zhang, J., Ngo, H.H., Guo, W., Hu, Z., Liang, S., Fan, J. and Liu, H. (2015). A review on the sustainability of CW for wastewater treatment: Design and operation. *Bioresource Technology* 175: 594-601.

Wurochekke, A.A., Mohamed, R.M.S.R., Halim, S.A.B.L., Kassim, A.H.M. and Hamdan, R.B. (2015). Sustainable extensive on-site CW for some bacteriological reduction in kitchen greywater. *Applied Mechanics and Materials* 773-774: 1199-1204.

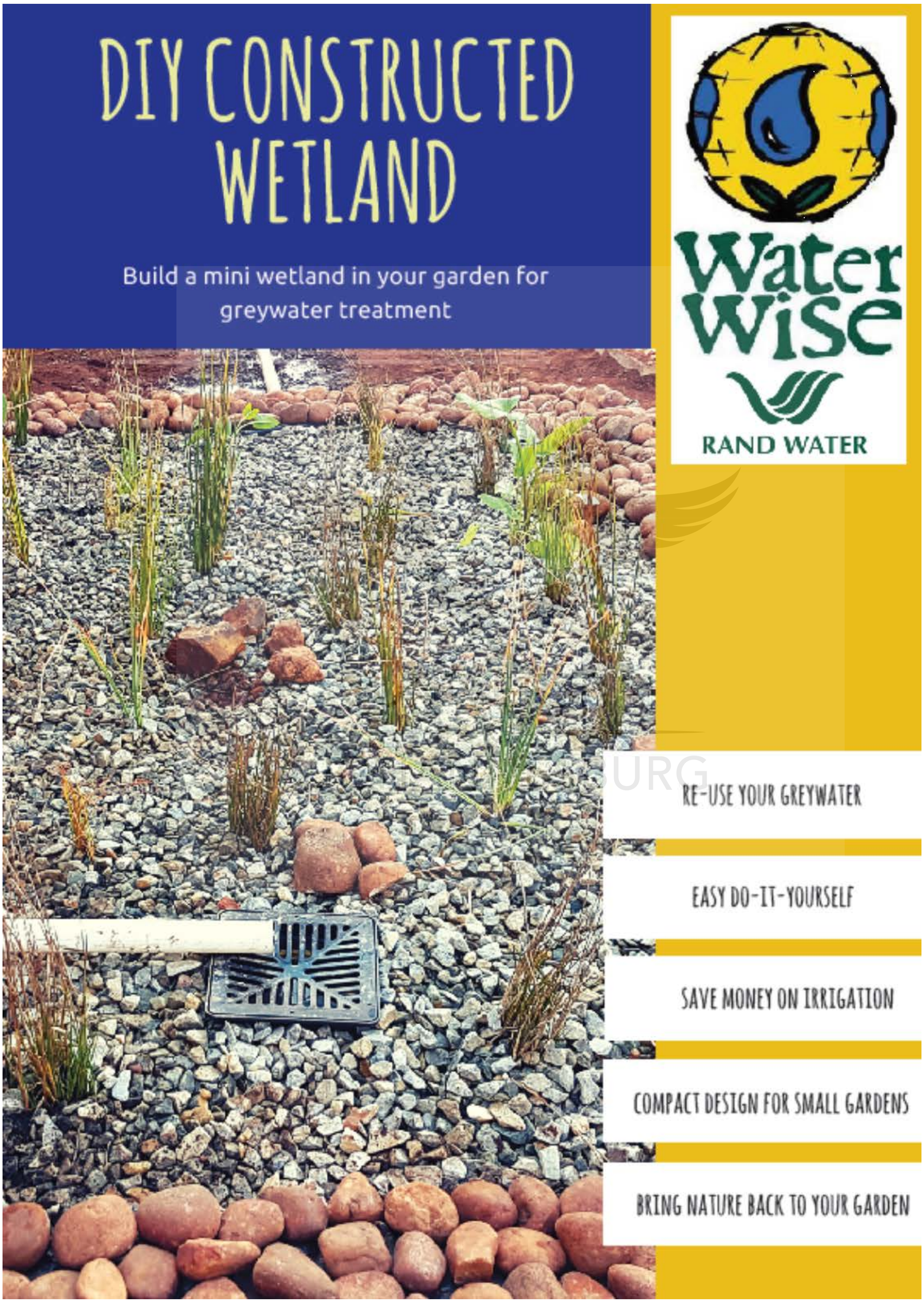
WWAP (United Nations World Water Assessment Programme) (2017). The United Nations World Water Development Report 2017. *Wastewater: The Untapped Resource*. Paris, UNESCO. ISBN: 978-92-3-100201-4.

Zhang, D.Q., Jinadasa, K.B.S.N, Gersberg, R.M., Liu, Y., Nga, W.J. and Tan, S.K. (2014). Application of CW for wastewater treatment in developing countries - A review of recent developments (2000-2013). *Journal of Environmental Management* 141: 116-131.

Zhou, Q., Zhu, H., Bañuelos, G., Yan, B., Liang, X., Yu, X., Cheng, X. and Chen, L. (2017). Effects of vegetation and temperature on nutrient removal and microbiology in horizontal sub-surface flow CW for treatment of domestic sewage. *Water, Air, and Soil Pollution* 228: 95-108.

Appendices

Appendix A: DIY Constructed Wetland: Build a mini wetland in your garden for greywater treatment



Appendix B: Full SANAS-accredited water quality reports

RAND WATER

SCIENTIFIC SERVICES
ANALYTICAL SERVICES
Barrage Road, Vereeniging
P.O.Box 3526 Vereeniging 1930 South Africa
Tel (016) 430 8400 Fax (016) 430 8455

Route 104 - Project on Greywater from Kitchen & Bathroom before & After Treatment for Samanta Stelli(R171317-SP435)
Samples for the week 21 Aug 2017 - 26 Aug 2017
Certificate of Analysis

Test Report: 2017/1604PROV
Report Date: 30 August 2017

ATTENTION:
Mrs Samanta Stelli
Rand Water - EMS
PO Box
J
1

Telephone number: 082 776 3197 / Ext 9371
Facsimile number: N/A

Our Reference	Your Reference	Sampled Date	Our Reference	Your Reference	Sampled Date	Our Reference	Your Reference	Sampled Date
3491734	P-EMS_AW_MO1	23-Aug-2017	3492258	P-EMS_AW_MO2	23-Aug-2017	3491663	P-EMS_AW_N1	23-Aug-2017
3492397	P-EMS_AW_N2	23-Aug-2017	3491649	P-EMS_AW_Z1	23-Aug-2017	3491659	P-EMS_AW_Z2	23-Aug-2017

RAND WATER

SCIENTIFIC SERVICES
ANALYTICAL SERVICES

Barrage Road, Vereeniging
P.O.Box 3526 Vereeniging 1930 South Africa
Tel (016) 430 8400 Fax (016) 430 8455

sanas T0013

Route 104 - Project on Greywater from Kitchen & Bathroom before & After Treatment for Samanta Stelli(R171317-SP435)
Samples for the week 04 Sep 2017 - 09 Sep 2017

Certificate of Analysis

Test Report: 2017/1701
Report Date: 21 September 2017

ATTENTION:

Mrs Samanta Stelli
Rand Water - EMS
PO Box

Telephone number: 082 776 3197 / Ext 9371
Facsimile number: N/A

Our Reference	Your Reference	Sampled Date	Our Reference	Your Reference	Sampled Date	Our Reference	Your Reference	Sampled Date
3505312	P-EMS_AW_MO1	6-Sep-2017	3505069	P-EMS_AW_MO2	6-Sep-2017	3505250	P-EMS_AW_N1	6-Sep-2017
3504806	P-EMS_AW_N2	6-Sep-2017	3505167	P-EMS_AW_Z1	6-Sep-2017	3504743	P-EMS_AW_Z2	6-Sep-2017

RAND WATER

SCIENTIFIC SERVICES
ANALYTICAL SERVICES

Barrage Road, Vereeniging
P.O.Box 3526 Vereeniging 1930 South Africa
Tel (016) 430 8400 Fax (016) 430 8455

sanas T0046

Route 104 - Project on Greywater from Kitchen & Bathroom before & After Treatment for Samanta Stelli(R171317-SP435)
Samples for the week 18 Sep 2017 - 23 Sep 2017

Certificate of Analysis

Test Report: 2017/1808
Report Date: 3 October 2017

ATTENTION:
Mrs Samanta Stelli
Rand Water - EMS
PO Box

Telephone number: 082 776 3197 / Ext 9371
Facsimile number: N/A

Our Reference	Your Reference	Sampled Date	Our Reference	Your Reference	Sampled Date	Our Reference	Your Reference	Sampled Date
3517952	P-EMS_AW_MO1	20-Sep-2017	3517822	P-EMS_AW_MO2	20-Sep-2017	3517926	P-EMS_AW_N1	20-Sep-2017
3517590	P-EMS_AW_N2	20-Sep-2017	3517903	P-EMS_AW_Z1	20-Sep-2017	3517560	P-EMS_AW_Z2	20-Sep-2017

RAND WATER

SCIENTIFIC SERVICES
ANALYTICAL SERVICES

Barrage Road, Vereeniging
P.O.Box 3526 Vereeniging 1930 South Africa
Tel (016) 430 8400 Fax (016) 430 8455

Route 104 - Project on Greywater from Kitchen & Bathroom before & After Treatment for Samanta Stelli(R171317-SP435)
Samples for the week 09 Oct 2017 - 14 Oct 2017

Test Report: 2017/1957
Report Date: 25 October 2017

Certificate of Analysis

ATTENTION:
Mrs Samanta Stelli
Rand Water - EMS
PO Box

Telephone number: 082 776 3197 / Ext 9371
Facsimile number: N/A

Our Reference	Your Reference	Sampled Date	Our Reference	Your Reference	Sampled Date	Our Reference	Your Reference	Sampled Date
3534895	P-EMS_AW_MO1	11-Oct-2017	3534677	P-EMS_AW_MO2	11-Oct-2017	3533872	P-EMS_AW_N1	11-Oct-2017
3533951	P-EMS_AW_N2	11-Oct-2017	3534298	P-EMS_AW_Z1	11-Oct-2017	3533849	P-EMS_AW_Z2	11-Oct-2017

SCIENTIFIC SERVICES
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Barrage Road, Vereeniging
P.O.Box 3526 Vereeniging 1930 South Africa
Tel (016) 430 8400 Fax (016) 430 8455

Route 104 - Project on Greywater from Kitchen & Bathroom before & After Treatment for Samanta Stelli(R171317-SP435)
Samples for the week 23 Oct 2017 - 28 Oct 2017

Test Report: 2017/2062
Report Date: 6 November 2017

Certificate of Analysis

ATTENTION:
Mrs Samanta Stelli
Rand Water - EMS
PO Box

Telephone number: 082 776 3197 / Ext 9371
Facsimile number: N/A

Our Reference	Your Reference	Sampled Date	Our Reference	Your Reference	Sampled Date	Our Reference	Your Reference	Sampled Date
3546600	P-EMS_AW_MO1	25-Oct-2017	3547382	P-EMS_AW_MO2	25-Oct-2017	3547130	P-EMS_AW_N1	25-Oct-2017
3546801	P-EMS_AW_N2	25-Oct-2017	3547370	P-EMS_AW_Z1	25-Oct-2017	3547119	P-EMS_AW_Z2	25-Oct-2017

SCIENTIFIC SERVICES
ANALYTICAL SERVICES
Barrage Road, Vereeniging
P.O.Box 3526 Vereeniging 1930 South Africa
Tel (016) 430 8400 Fax (016) 430 8455

RAND WATER

sanas T0033

Route 104 - Project on Greywater from Kitchen & Bathroom before & After Treatment for Samanta Stelli(R171317-SP435)
Samples for the week 06 Nov 2017 - 11 Nov 2017

Test Report: 2017/2165
Report Date: 30 November 2017

Certificate of Analysis

ATTENTION:
Mrs Samanta Stelli
Rand Water - EMS
PO Box

Telephone number: 082 776 3197 / Ext 9371
Facsimile number: N/A

Our Reference	Your Reference	Sampled Date	Our Reference	Your Reference	Sampled Date	Our Reference	Your Reference	Sampled Date
3559311	P-EMS_AW_MO1	14-Nov-2017	3559123	P-EMS_AW_MO2	14-Nov-2017	3558165	P-EMS_AW_N1	14-Nov-2017
3559155	P-EMS_AW_N2	14-Nov-2017	3558135	P-EMS_AW_Z1	14-Nov-2017	3559087	P-EMS_AW_Z2	14-Nov-2017

RAND WATER

SCIENTIFIC SERVICES
ANALYTICAL SERVICES

Barrage Road, Vereeniging
P.O.Box 3526 Vereeniging 1930 South Africa
Tel (016) 430 8400 Fax (016) 430 8455

sanas T0033

Route 104 - Project on Greywater from Kitchen & Bathroom before & After Treatment for Samanta Stelli(R171317-SP435)
Samples for the week 20 Nov 2017 - 25 Nov 2017

Test Report: 2017/2277
Report Date: 5 December 2017

Certificate of Analysis

ATTENTION:
Mrs Samanta Stelli
Rand Water - EMS
PO Box

Telephone number: 082 776 3197 / Ext 9371
Facsimile number: N/A

Our Reference	Your Reference	Sampled Date	Our Reference	Your Reference	Sampled Date	Our Reference	Your Reference	Sampled Date
3570956	P-EMS_AW_MO1	22-Nov-2017	3571815	P-EMS_AW_MO2	22-Nov-2017	3571188	P-EMS_AW_N1	22-Nov-2017
3571882	P-EMS_AW_N2	22-Nov-2017	3571179	P-EMS_AW_Z2	22-Nov-2017			

RAND WATER

SCIENTIFIC SERVICES
ANALYTICAL SERVICES

Barrage Road, Vereeniging
P.O.Box 3526 Vereeniging 1930 South Africa
Tel (016) 430 8400 Fax (016) 430 8455

sanas T0033

Route 104 - Project on Greywater from Kitchen & Bathroom before & After Treatment for Samanta Stelli(R171317-SP435)
Samples for the week 04 Dec 2017 - 09 Dec 2017

Certificate of Analysis

Test Report: 2017/2371
Report Date: 21 December 2017

ATTENTION:
Mrs Samanta Stelli
Rand Water - EMS
PO Box

Telephone number: 082 776 3197 / Ext 9371
Facsimile number: N/A

Our Reference	Your Reference	Sampled Date	Our Reference	Your Reference	Sampled Date	Our Reference	Your Reference	Sampled Date
3584148	P-EMS_AW_MO1	6-Dec-2017	3585372	P-EMS_AW_MO2	6-Dec-2017	3585413	P-EMS_AW_N1	6-Dec-2017
3584954	P-EMS_AW_N2	6-Dec-2017	3584493	P-EMS_AW_Z1	6-Dec-2017	3585381	P-EMS_AW_Z2	6-Dec-2017

RAND WATER

SCIENTIFIC SERVICES
ANALYTICAL SERVICES

Barrage Road, Vereeniging
P.O.Box 3526 Vereeniging 1930 South Africa
Tel (016) 430 8400 Fax (016) 430 8455

sanas T0033

Route 104 - Project on Greywater from Kitchen & Bathroom before & After Treatment for Samanta Stelli(R171317-SP435)
Samples for the week 26 Mar 2018 - 31 Mar 2018

Test Report: 2018/1279
Report Date: 13 April 2018

Certificate of Analysis

ATTENTION:
Mrs Samanta Stelli
Rand Water - EMS
PO Box

Telephone number: 082 776 3197 / Ext 9371
Facsimile number: N/A

Our Reference	Your Reference	Sampled Date	Our Reference	Your Reference	Sampled Date	Our Reference	Your Reference	Sampled Date
3691021	P-EMS_AW_MO1	28-Mar-2018	3691179	P-EMS_AW_N1	28-Mar-2018	3690902	P-EMS_AW_N2	28-Mar-2018
3690547	P-EMS_AW_Z1	28-Mar-2018	3691166	P-EMS_AW_Z2	28-Mar-2018			

RAND WATER

SCIENTIFIC SERVICES
ANALYTICAL SERVICES

Barrage Road, Vereeniging
P.O.Box 3526 Vereeniging 1930 South Africa
Tel (016) 430 8400 Fax (016) 430 8455

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T0033

Route 104 - Project on Greywater from Kitchen & Bathroom before & After Treatment for Samanta Stelli(R171317-SP435)
Samples for the week 23 Apr 2018 - 28 Apr 2018

Certificate of Analysis

Test Report: 2018/1625
Report Date: 11 May 2018

ATTENTION:
Mrs Samanta Stelli
Rand Water - EMS
PO Box

Telephone number: 082 776 3197 / Ext 9371
Facsimile number: N/A

Our Reference	Your Reference	Sampled Date	Our Reference	Your Reference	Sampled Date	Our Reference	Your Reference	Sampled Date
3715606	P-EMS_AW_MO1	26-Apr-2018	3715401	P-EMS_AW_MO2	26-Apr-2018	3715411	P-EMS_AW_N1	26-Apr-2018
3715097	P-EMS_AW_N2	26-Apr-2018	3715406	P-EMS_AW_Z2	26-Apr-2018			

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T0033

Route 104 - Project on Greywater from Kitchen & Bathroom before & After Treatment for Samanta Stelli(R171317-SP435)
Samples for the week 28 May 2018 - 02 Jun 2018

Certificate of Analysis

Test Report: 2018/2000
Report Date: 8 June 2018

ATTENTION:
Mrs Samanta Stelli
Rand Water - EMS
PO Box

Telephone number: 082 776 3197 / Ext 9371
Facsimile number: N/A

Our Reference	Your Reference	Sampled Date	Our Reference	Your Reference	Sampled Date	Our Reference	Your Reference	Sampled Date
3749077	P-EMS_AW_MO1	30-May-2018	3748893	P-EMS_AW_MO2	30-May-2018	3748967	P-EMS_AW_N1	30-May-2018
3749634	P-EMS_AW_N2	30-May-2018	3749281	P-EMS_AW_Z1	30-May-2018	3748962	P-EMS_AW_Z2	30-May-2018

Appendix C: Paired samples *t* - test results

Appendix C-1. Paired samples *t* - test results (two-tailed *P* - and *t* - values; mean ± SE) for a comparison of pre- and post-treatment of domestic greywater with CW of various physico-chemical and microbiological parameters, for eleven sampling trials, for the MO-AW at the Environmental Services Department, Zwartkopjes, Rand Water (*n* = 11; *d.f.* = 10). Bolded *P* - values are regarded as significant at the *P* = 0.05 level.

Water Quality Parameter	Unit	Paired sample *t*-test results		
		P	***t***	**Mean difference ± SE**
DO	mg/L O_2	0.13	1.65	0.49 ± 0.3
Ca Hardness	mg/L $CaCO_3$	0.23	-1.28	-25.00 ± 19.54
Mg Hardness	mg/L $CaCO_3$	0.37	-0.95	-6.27 ± 6.61
Cl	mg/L	0.98	-0.03	-0.27 ± 8.44
NO_3	mg/L as N	0.55	0.63	1.02 ± 1.69
SO_4	mg/L	0.002	4.09	7.71 ± 1.88
B	µg/L	0.18	1.44	35.45 ± 24.62
Ca	mg/L	0.24	-1.26	-9.91 ± 7.85
K	mg/L	0.27	1.16	3.08 ± 2.66
Mg	mg/L	0.29	-1.09	-1.69 ± 1.54
Na	mg/L	0.79	-0.264	-1.18 ± 4.47
Conductivity	mS/m	0.06	-2.17	-14.45 ± 6.68
Mg Alkalinity (M Alk)	mg/L $CaCO_3$	0.28	-1.13	-29.55 ± 26.09
pH	-	0.14	-1.61	-1.04 ± 0.64
Temperature	°C	0.32	1.05	1.94 ± 1.86
TDS (TDS_CALC)	mg/L	**0.009**	-3.23	-98.73 ± 30.54
TP	mg/L	**0.002**	4.28	1.39 ± 0.32
Turbidity	NTU	**<0.05**	5.99	667.18 ± 111.38
E.coli	MPN/100mL	**0.035**	2.44	3733521.64 ± 1529316.61
Oil and grease	mg/L	**0.001**	4.52	786.40 ± 174.19
TOC	mg/L as C	**<0.05**	7.16	268.59 ± 37.50

Appendix C-2. Paired samples *t* - test results (two-tailed *P* - and *t* - values; mean ± SE) for a comparison of pre- and post-treatment of domestic greywater with CW of various physico-chemical and microbiological parameters, for eleven sampling trials, for the N-AW at the Environmental Services Department, Zwartkopjes, Rand Water (*n* = 11; *d.f.* = 10). Bolded *P* - values are regarded as significant at the *P* = 0.05 level.

Water Quality Parameter	Unit	Paired sample *t*-test results		
		P	***t***	**Mean difference ± SE**
DO	mg/L O_2	0.98	-0.03	-0.01 ± 0.28
Ca Hardness	mg/L $CaCO_3$	**0.004**	-3.67	-37.82 ± 10.31
Mg Hardness	mg/L $CaCO_3$	0.13	-1.65	-10.82 ± 6.56
Cl	mg/L	0.85	-0.19	-1.09 ± 5.57
NO_3	mg/L as N	0.22	1.30	0.67 ± 0.51
SO_4	mg/L	0.11	-1.78	-23.38 ± 13.12
B	µg/L	0.026	2.62	59.82 ± 22.86
Ca	mg/L	**0.004**	-3.69	-15.18 ± 4.11
K	mg/L	0.97	-0.034	-0.03 ± 0.08
Mg	mg/L	0.14	-1.63	-2.01 ± 1.24
Na	mg/L	0.86	-0.18	-0.82 ± 4.44
Conductivity	mS/m	**0.002**	-4.23	-13.82 ± 3.27
Mg Alkalinity (M Alk)	mg/L $CaCO_3$	**0.004**	-3.72	-56.00 ± 15.05
pH	-	**<0.05**	-7.53	-1.05 ± 0.14
Temperature	°C	0.42	0.84	0.24 ± 0.28
TDS (TDS_CALC)	mg/L	**0.002**	-4.21	-75.91 ± 18.01
TP	mg/L	**0.05**	2.19	0.33 ± 0.15
Turbidity	NTU	**0.001**	4.42	585.55 ± 132.47
E.coli	MPN/100mL	0.15	1.56	17892259.64 ± 11507564.95
Oil and grease	mg/L	**<0.05**	6.59	1100.22 ± 166.77
TOC	mg/L as C	**<0.05**	5.38	133.39 ± 24.8

Appendix C-3. Paired samples *t* - test results (two-tailed *P* - and *t* - values; mean ± SE) for a comparison of pre- and post-treatment of domestic greywater with CW of various physico-chemical and microbiological parameters, for eleven sampling trials, for the Z-AW at the Environmental Services Department, Zwartkopjes, Rand Water (*n* = 11; *d.f.* = 10). Bolded *P* - values are regarded as significant at the *P* = 0.05 level.

Water Quality Parameter	Unit	Paired sample *t*-test results		
		P	***t***	**Mean difference ± SE**
DO	mg/L O_2	**0.001**	-4.90	-1.67 ± 0.34
Ca Hardness	mg/L $CaCO_3$	0.42	-0.84	-23.36 ± 27.89
Mg Hardness	mg/L $CaCO_3$	0.79	-0.27	-1.98 ± 7.25
Cl	mg/L	0.34	1.01	5.33 ± 5.28
NO_3	mg/L as N	0.09	-1.85	-0.11 ± 0.06
SO_4	mg/L	0.09	-1.82	-33.77 ± 18.51
B	µg/L	0.09	1.83	31.64 ± 17.31
Ca	mg/L	0.42	-0.84	-9.50 ± 11.29
K	mg/L	0.85	0.20	0.17 ± 0.86
Mg	mg/L	0.77	-0.29	-0.53 ± 1.77
Na	mg/L	0.17	1.48	7.99 ± 5.39
Conductivity	mS/m	0.84	0.21	1.77 ± 8.56
Mg Alkalinity (M Alk)	mg/L $CaCO_3$	0.48	0.74	25.91 ± 34.88
pH	-	0.10	-1.80	-1.60 ± 0.89
Temperature	°C	0.16	-1.52	-3.72 ± 2.45
TDS (TDS_CALC)	mg/L	0.74	-0.34	-16.00 ± 48.81
TP	mg/L	0.06	-2.08	-0.02 ± 0.12
Turbidity	NTU	0.36	0.96	66.12 ± 68.98
E.coli	MPN/100mL	0.13	1.63	674110.45 ± 413289.69
Oil and grease	mg/L	0.06	2.16	25.24 ± 11.67
TOC	mg/L as C	**0.007**	3.38	15.43 ± 4.56